

CHAPTER NO.- 01

Understand the Construction and Working of Power Electronic Devices

Learning Objectives:

- 1.1 Construction, Operation, V-I characteristics & application of power diode, SCR, DIAC, TRIAC, Power MOSFET, GTO & IGBT*
- 1.2 Two transistor analogy of SCR.*
- 1.3 Gate characteristics of SCR.*
- 1.4 Switching characteristic of SCR during turn on and turn off.*
- 1.5 Turn on methods of SCR.*
- 1.6 Turn off methods of SCR (Line commutation and Forced commutation)*
 - 1.6.1 Load Commutation*
 - 1.6.2 Resonant pulse commutation*
- 1.7 Voltage and Current ratings of SCR.*
- 1.8 Protection of SCR*
 - 1.8.1 Over voltage protection*
 - 1.8.2 Over current protection*
 - 1.8.3 Gate protection*
- 1.9 Firing Circuits*
 - 1.9.1 General layout diagram of firing circuit*
 - 1.9.2 R firing circuits*
 - 1.9.3 R-C firing circuit*
 - 1.9.4 UJT pulse trigger circuit*
 - 1.9.5 Synchronous triggering (Ramp Triggering), Design of Snubber Circuits*

1.0. INTRODUCTION:

The Power electronics have eased the concept of power control. Power electronics signifies the word power electronics and control or we can say the electronic that deal with power equipment for power control.

Power electronics based on the switching of power semiconductor devices. With the development of power semiconductor technology, the power handling capabilities and switching speed of power devices increased.

Power Semiconductor Devices :

1. Thyristors
2. Transistors
3. Power diodes

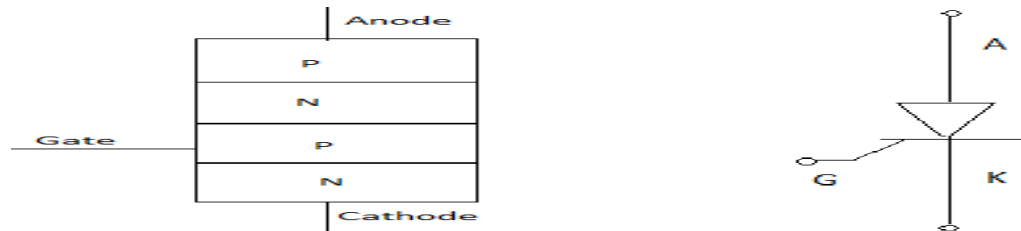
1.1. Construction, Operation, V-I characteristics & application of SCR:

Thyristors

Thyristor is a four layer three junction p-n p-n semiconductor switching device. It has 3

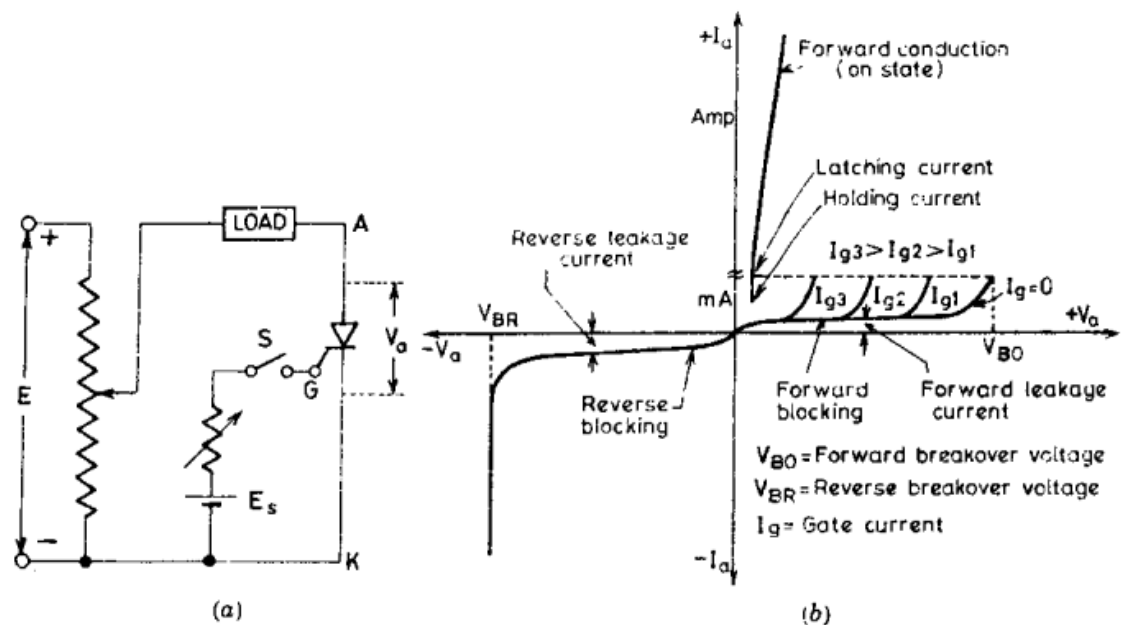
terminals these are anode, cathode and gate. SCRs are solid state device, so they are compact, possess high reliability and have low loss.

SCR is made up of silicon, it act as a rectifier; it has very low resistance in the forward direction and high resistance in the reverse direction. It is a unidirectional device.



Static V-I characteristics of a Thyristor

The circuit diagram and V-I characteristics of a Thyristor is as shown below. Where Anode and cathode are connected to main source voltage through the load. The gate and cathode are fed from source E_s .



Where

V_{BO} = Forward break over voltage

V_{BR} = Reverse break over voltage

I_g = Gate current

V_a = Anode voltage across the thyristor terminal A,K.

I_a = Anode current

The SCR have 3 modes of operation:

1. Reverse blocking mode
2. Forward blocking mode (off state)

3. Forward conduction mode (on state)

Reverse Blocking Mode

- When cathode of the thyristor is made positive with respect to anode with switch open thyristor is reverse biased. Junctions J_1 and J_2 are reverse biased where junction J_2 is forward biased. The device behaves as if two diodes are connected in series with reverse voltage applied across them.
- A small leakage current of the order of few mA only flows. As the thyristor is reverse biased and in blocking mode. It is called as acting in reverse blocking mode of operation.
- Now if the reverse voltage is increased, at a critical breakdown level called reverse breakdown voltage V_{BR} , an avalanche occurs at J_1 and J_3 and the reverse current increases rapidly. As a large current associated with V_{BR} and hence more losses to the SCR. This results in Thyristor damage as junction temperature may exceed its maximum temperature rise.

Forward Blocking Mode

- When anode is positive with respect to cathode, with gate circuit open, thyristor is said to be forward biased. Thus junction J_1 and J_3 are forward biased and J_2 is reverse biased. As the forward voltage is increased junction J_2 will have an avalanche breakdown at a voltage called forward break over voltage V_{BO} .
- When forward voltage is less than V_{BO} thyristor offers high impedance. Thus a thyristor acts as an open switch in forward blocking mode.

Forward Conduction Mode

- Here thyristor conducts current from anode to cathode with a very small voltage drop across it. So a thyristor can be brought from forward blocking mode to forward conducting mode:
 1. By exceeding the forward breakover voltage.
 2. By applying a gate pulse between gate and cathode.
- During forward conduction mode of operation thyristor is in on state and behave like a close switch. Voltage drop is of the order of 1 to 2mV. This small voltage drop is due to ohmic drop across the four layers of the device.

1.1.Construction, Operation, V-I characteristics & application of power diode :

1.Power Diodes:

Basic structure of Power Diode:

- Power diode consists of three layers. Top layer is a heavily doped P^+ layer. Middle layer is lightly doped n^- layer and the last layer is a heavily doped n^+ layer.
- The heavily doped p^+ layer act as an anode. Last layer of the heavily doped n^+ act as a cathode. Middle layer of lightly doped n^- is known as a drift layer. The thickness of the drift layer depends on the required breakdown voltage.
- The breakdown voltage increases with an increase in the width of the drift layer. Resistivity of this layer is high because of the low level of doping.
- If the width of the drift layer increased, then the on-state voltage drop increase therefore power loss is more.
- The junction is form between the anode layer (p^+) and drift layer (n^-). The cross-section area of the diode depends on the magnitude of current to be handled. Higher the current to handle, more the area required.

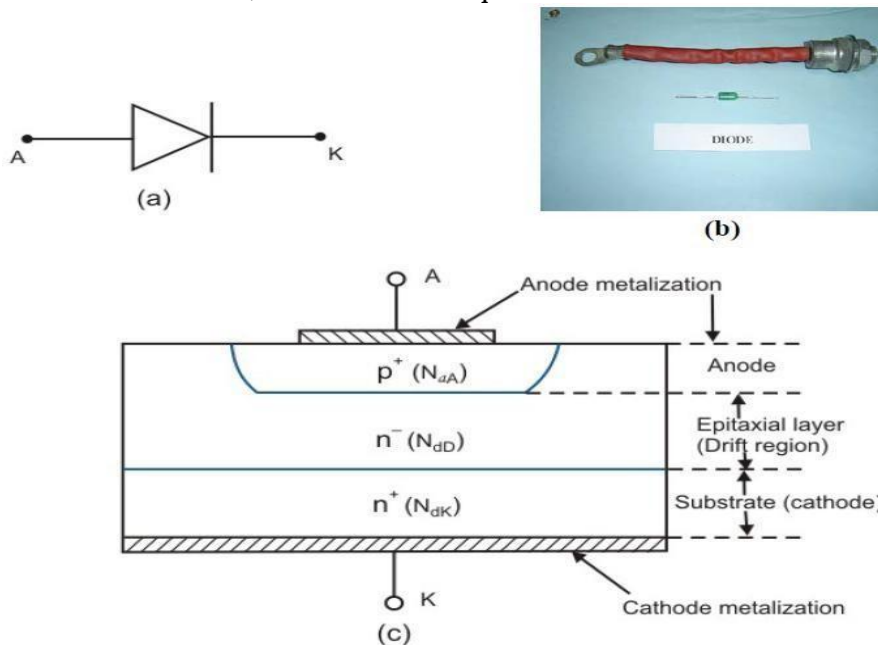
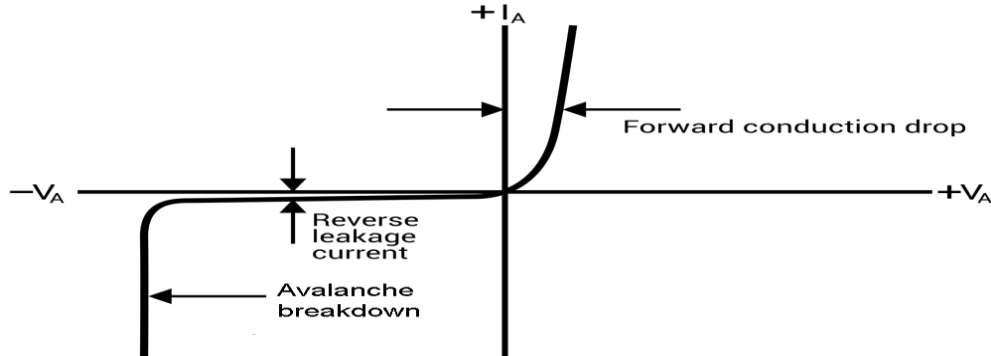


Fig.1 : Diagram of a power; (a) circuit symbol (b) photograph; (c) schematic cross

Operating Principle of Power diode:

- The operating principle of power diode is same as the conventional PN junction diode.
- A diode conducts when the anode voltage is higher than the cathode voltage. The forward voltage drop across the diode is very low around 0.5V to 1.2V. In this region, the diode works as a forward characteristic.
- If the cathode voltage is higher than the anode voltage, then the diode works as blocking mode. In this mode, diode works according to the reverse characteristic.

I-V characteristic of Power Diode:



The I-V characteristic of power diode is as shown in the figure.

- The forward current increase linearly with an increase in forward voltage.
- A very small amount of leakage current flows in the reverse bias (blocking mode).
- The leakage current is independent of the applied reverse voltage.
- The leakage current flows due to the minority charge carriers. When the reverse voltage reaches the reverse breakdown voltage, avalanche breakdown occurs. Once the reverse breakdown occurs, the reverse current increase drastically with small increase in reverse voltage. The reverse current can control by an external circuit.
- In the case of reverse breakdown, As the voltage and current of the diode are large, the power dissipation is dangerously high and it can destroy the device.

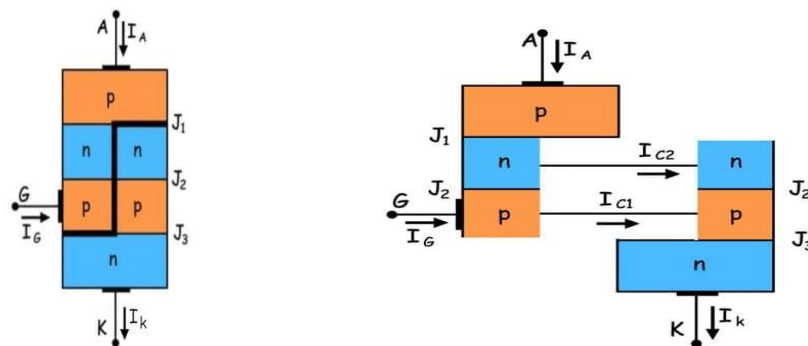
Application of Power Diode in Power Electronics:

- High voltage rectifier
- As freewheeling diode
- As feedback diode

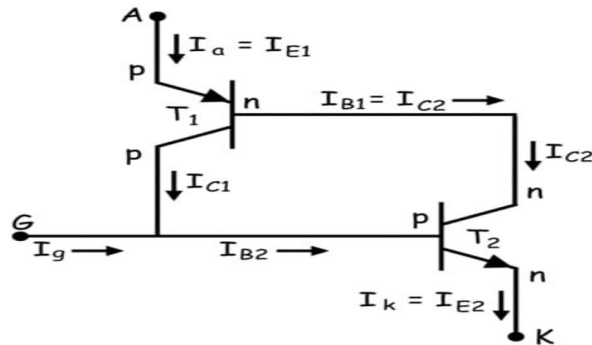
1.2 Two transistor analogy of SCR:

Basic operating principle of SCR, can easily be understood by the two transistor model of SCR, as it is a combination of p and n layers.

This is a p-n-p-n thyristor. i.e. one p-n-p transistor with J1 and J2 junctions and another n-p-n is with J2 and J3 junctions as shown in figure below.



The relation between the collector current and emitter current is shown below



from the above diagram

I_a = Anode current, I_k = cathode current, I_g = Gate

current I_{e1} = emitter current of transistor T_1

I_{c1} = collector current of

Transistor T_1

I_{b1} = Base current of transistor T_1

I_{e2} = emitter current of transistor

T_2 I_{c2} = collector current of

transistor T_2

I_{b2} = Base current of

transistor T_2 α = current

gain of transistor

From the above fig. it is clear that collector current of T_1 is equal to the base current of T_2 and vice versa.

Mathematically: $I_{c1} = I_{b2}$ & $I_{b1} = I_{c2}$

Also $I_k = I_a + I_g$ (i)

From transistor analysis $I_{b1} = I_{e1} - I_{c1}$ ----- (ii)

Also current gain, $\alpha = I_{c1} / I_{e1}$

$I_{c1} = \alpha I_{e1}$ ----- (iii)

Substituting the equation (iii) in

equation(ii) we get

$$I_{b1} = I_{e1} - \alpha_1 I_{e1}$$

$$I_{b1} = I_{e1}(1-\alpha_1) \text{ ----- (iv)}$$

From the fig. it is clear that $I_a = I_{e1}$

$$\text{So } I_{b1} = I_a(1-\alpha_1) \text{ ----- (v)}$$

Current gain of transistor T_2 , $\alpha_2 = I_{c2} / I_{e2}$

$$I_{c2} = \alpha_2 I_{e2}$$

$$I_{c2} = \alpha_2 I_k \text{ ----- (vi) (as } I_{e2} = I_k)$$

From the above fig. $I_{b1} = I_{c2}$

Equating equation (v) and (vi) we

get $I_a(1-\alpha_1) = \alpha_2 I_k$

$$I_a - \alpha_1 I_a = \alpha_2(I_a + I_g) \text{ (as } I_k =$$

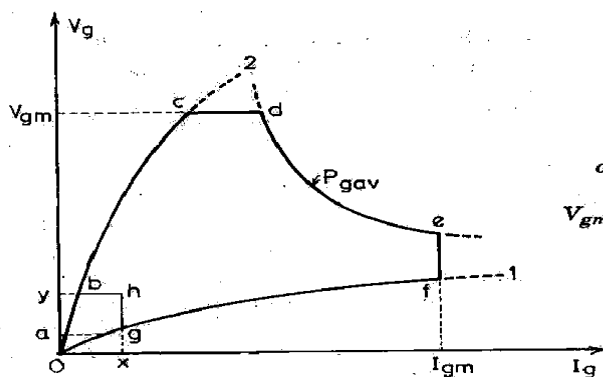
$$I_a + I_g) I_a - \alpha_1 I_a - \alpha_2 I_a = \alpha_2 I_g$$

$$I_a = \alpha_2 I_g / (1 - \alpha_1 - \alpha_2) \text{ ----- (vii)}$$

The above is the anode current of a Thyristor.

1.3 Gate characteristics of SCR:

The gate characteristics drawn in between gate voltage and gate current of a SCR.



$\alpha y, \alpha x$ — Minimum gate voltage and current to trigger an SCR.
 V_{gm}, I_{gm} — Maximum permissible gate voltage and current.
 oa — Non-triggering gate voltage.

Fig. 4.9 Forward gate characteristics of thyristor.

V_g = +ve gate to cathode voltage.

I_g = +ve gate to cathode current.

As the gate cathode characteristic of a thyristor is a p-n junction, gate characteristic of the device is similar to diode. Curve 1 the lowest voltage values that must be applied to turn on the SCR.

Curve 2 highest possible voltage values that can be safely applied to get circuit.

V_{gm} = Maximum limit for gate voltage .

I_{gm} = Maximum limit for gate current.

P_{gav} = Rated gate power dissipation for each SCR.

These limits should not be crossed in order to avoid the permanent damage of the device junction J3.

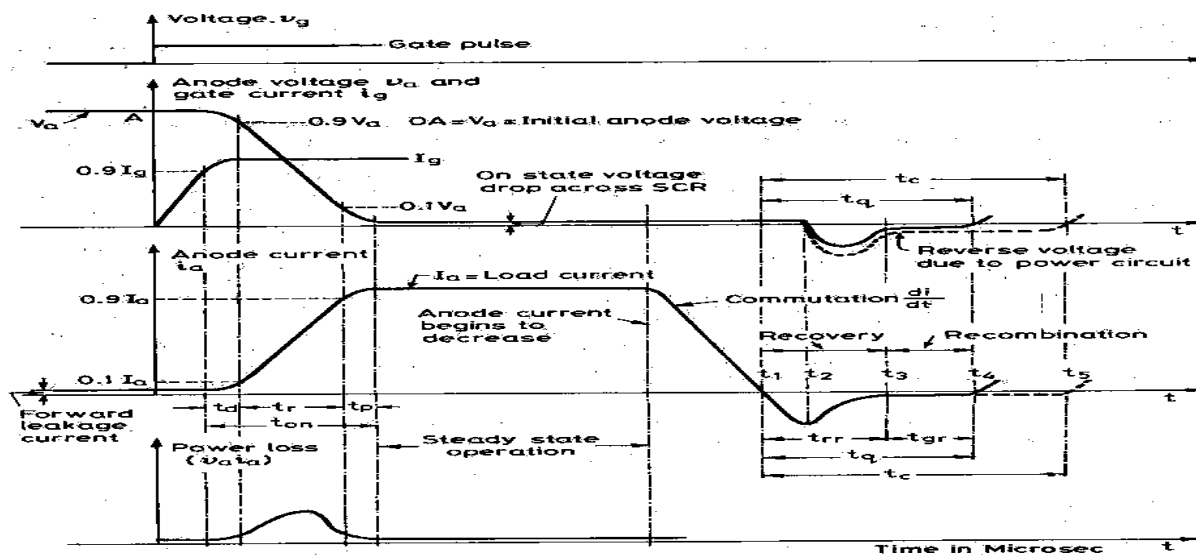
OY = Minimum limit of gate voltage to turn

ON .OX = minimum limit of gate current to turn ON.

If V_{gm} , I_{gm} , P_{gav} are exceeded the thyristor will damage so the preferred gatedrive area of SCR is bcdefghb.

oa = The non-triggering gate voltage .

1.4 Switching characteristic of SCR during turn on and turn off:



The time variation of voltage across the thyristor and current through it during turn on and turnoff process gives the dynamic or switching characteristic of SCR.

(a) Switching characteristics during turn on process of Thyristors:

It is the time during which it changes from forward blocking state to ON state. Total turn on time is divided into 3 intervals:

- ☐ Delay time
- ☐ Rise time
- ☐ Spread time

Delay time(t_d)

If I_g and I represent the final value of gate current and anode current.

Then the delay time can be explained as time during which

- ☐ Gate current 0.9 I_g to 0.1 I_a .
- ☐ Anode voltage falls from V_a to 0.9 V_a .
- ☐ Anode current rises from forward leakage current to 0.1 I_a .

Rise time (t_r)

Time during which

- ☐ Anode current rises from 0.1 I_a to 0.9 I_a
- ☐ Forward blocking voltage falls from 0.9 V_a to 0.1 V_a . V_a is the initial forward blocking voltage.

Spread time (t_p)

- ☐ Time taken by the anode current to rise from 0.9 I_a to I_a .
- ☐ Time for the forward voltage to fall from 0.1 V_o to on state voltage drop of 1 to 1.5V.

(b) Switching characteristics during turn off process of Thyristors:

- Thyristor turn off means it changed from ON to OFF state. This process which is applied is called as turn off process or commutation.
- Once thyristor is ON there is no role of gate. As we know thyristor can be made turn OFF by reducing the anode current below the latching current.
- The turn off time can be different as the instant anode current becomes zero to the instant when SCR regains its forward blocking capability.

The turn off time is divided into two intervals i.e. $t_{off} = t_{rr} + t_{gr}$

a) Reverse recovery time (t_{rr})

b) Gate recovery time (t_{gr})

a) Reverse recovery time (t_{rr}) :-

- It is defined as the time between the instant forward thyristor current becomes zero & that instant reverse recovery current decays to 25 percentage of its reverse peak.
- Reverse recover process is the process by which the excessive charge carriers from upper P layer to the bottom N layer is removed, the time taken by this process is known as reverse recovery time (t_{rr})

b) Gate recovery time (t_{gr})

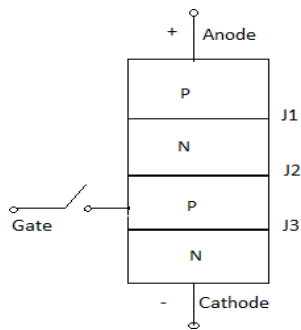
- It is the process by which the excess charge carriers from the junction J2 is removed is called as gate recovery process. The time taken for doing this process is called as gate recovery time.

1.5 Turn on methods of SCR:

There are five methods are adopted to turn on the SCR that are :-

1. Forward voltage triggering
2. Gate triggering
3. dv/dt triggering
4. Light triggering
5. Temperature triggering

1. Forward voltage triggering



A forward voltage is applied between anode and cathode with gate circuit open.

- Junction $J1$ and $J3$ is forward biased and Junction $J2$ is reverse biased.
- As the anode to cathode voltage is increased breakdown of the reverse biased junction $J2$ occurs. This is known as avalanche breakdown and the voltage at which this phenomena occurs is called forward breakover voltage.
- The conduction of current continues even if the anode cathode voltage reduces below VBO till I_a will not go below I_h . Where I_h is the holding current for the thyristor.

2. Gate triggering

- In this type of triggering a forward voltage is given between the anode & cathode & simultaneously a positive gate pulse is applied in between gate & cathode so the thyristor can be turn on .
- It is due to that when a positive voltage is applied between the gate & cathode of a forward biased SCR the charge carriers are injected into the inner layer their by reducing the depletion layer as the forward voltage increase & giving the positive gate pulse the thyristor gate turned on.

3. dv/dt triggering

- When forward voltage is applied between anode & cathode of SCR with gate circuit open, the junction j1 & j3 are forward biased & junction j2 is reverse biased so in this case junction j1 & j3 acts like two plates of capacitor & j2 acts like a insulating medium between the two plates.
- The current flowing the capacitor is given by the anode current so we know that current flowing through a capacitor
- $I = dq/dt$
 $Q = C.V$

$$I = d(CV)/dt \\ = V \cdot dc/dt + C \cdot dv/dt$$

$$I_a = C \cdot dv/dt$$

Where, C = capacitance of the capacitor which is constant as dv/dt goes on increasing, it also increases & at a certain stage then it starts conducting

3. Light triggering

- An SCR turned on by light radiation is called as light activated silicon-controlled rectifier (LASCR)
- This type of triggering is employed for phase-controlled converter in HVDC transmission line.
- In this method light rays with appropriate wavelength and intensity are allowed to break the junction j2.
- This type of SCR consists of a niche in the inner layer therefore when light strikes on this niche the electron-hole pairs are generated at the junction j2 which provides additional charge carriers at the junctions & it leads to turn on the SCR

4. Temperature Triggering

- During forward blocking mode most of the applied voltage appears across reverse biased junction j2. This voltage across j2 associated with large current, it would increase the temperature of this junction, with increase in temperature the width of the depletion layer decreases. At a high temperature the depletion layer will vanish so the thyristor will turn on.

1.6 Turn off methods of SCR (Line commutation and Forced commutation)

- The turn off process of a thyristor means bringing the device from forward conduction state to forward blocking state.
- The thyristor turned off requires that its anode current falls below the holding current & a reverse voltage is applied to the thyristor for a sufficient time to recover the forward blocking state.
- Commutation is defined as the process of turning off the thyristor.
- Once the thyristor starts conducting gate loses the control over the device therefore

external means may have to be added to commutate the thyristor.

1. Latching current

- It is the minimum value of anode current which is most attain during turn on process to maintain the conduction when the gate signal is removed.

2. Holding current

- It is the minimum value of anode current below which it must fall turning off thyristor.

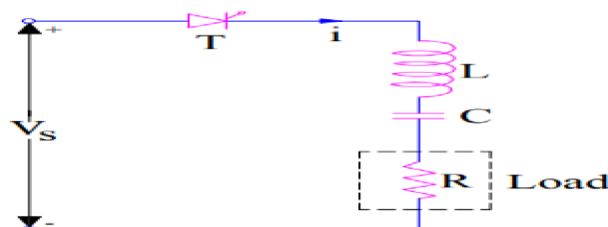
1.6. Turn off methods of SCR (Line commutation and Forced commutation)

Commutation is a process of turning off a Thyristor.

Classification of Commutation Methods

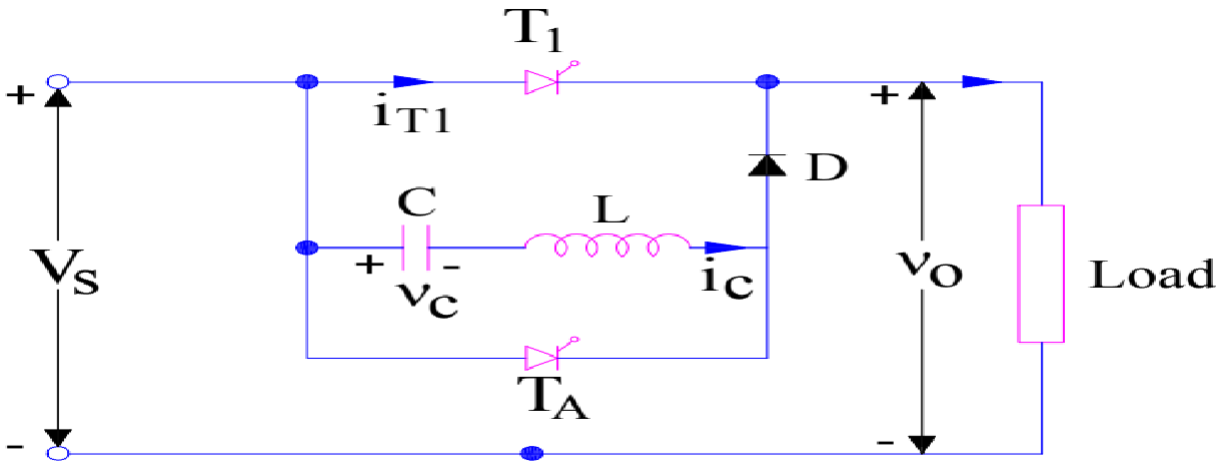
1. class A commutation or load commutation
2. class B commutation or resonant pulse commutation
3. class C commutation or complementary commutation.
4. class D commutation or impulse commutation
5. class E commutation or external pulse commutation
6. class F commutation or line commutation.

1.6.1 Class A commutation or load commutation



- Class A commutation is also known as load commutation, self-commutation or resonant commutation.
- For achieving load commutation of a thyristor the commutative element L & C are connected in series with load R , and for higher value, R is connected across the capacitor.
- The essential requirement of this circuit is that the overall circuit must be under damped.
- When the circuit is energized from DC source the current will rise to maximum value & then begins to fall.
- When the current decreases to zero & tends to reverse the thyristor is turned off at its own means the circuit shows that the current has the natural tendency to decrease to zero.

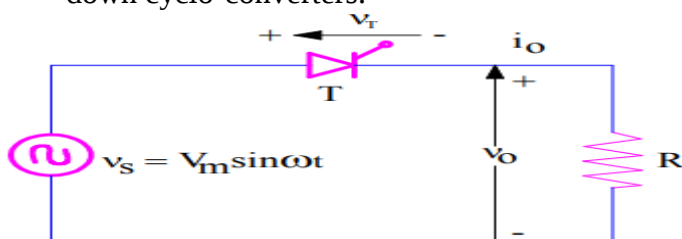
1.6.2. Class B commutation or resonant pulse commutation



- Initially the capacitor C charges to a voltage V_S with left hand positive at that condition the thyristor T_1 & T_A are off.
- Now the thyristor is turned on at $t = t_1$ thyristor T_1 gets turned on so the current i_o is flowing through the load so at that instant $i_o = i_{T_1} = I_1$ & $v_C = V_S$.
- To commute the main thyristor T_1 the auxiliary thyristor T_A is gated at $t = t_1$.
- With T_A on a resonant current i_C begins to flow from $-L$ & back to C ($C \rightarrow T_A \rightarrow L \rightarrow C$). So the i_C current will be $i_C = -I_p \sin \omega t$, the $-$ sign before I_p is due to the opposition of current as marked before.
- When a reverse current flows through T_A , T_1 gets off automatically.
- Now the polarity of the capacitor gets changed so in that case the diode gets turned on & the capacitor charges the voltage $-V_S$. now the capacitor current flows through ($C \rightarrow L \rightarrow D \rightarrow T_1 \rightarrow C$)
- In this case the capacitor current is opposite to the thyristor current so the thyristor T_1 gets turned off.
- The class B commutation is also known as resonant pulse commutation or current commutation.

1.6.3. Class F commutation or Line or Natural Commutation

- Natural or Line commutation is a Class-F SCR commutation technique in which, a thyristor is turned off due to natural current zero and voltage reversal after every half cycle.
- This commutation method is only applicable for AC circuit and mostly used in Phase-Controlled Converters, Line-Commutated Inverters, AC voltage controllers and Step-down cyclo-converters.



- Let us assume that, thyristor T is fired or gated at firing angle equal to zero i.e. $\omega t = 2n\pi$ where n is 0,1,2,3.....,
- Since load is resistive, with zero degree firing angle, the SCR behaves like a diode.
- During positive half cycle, the SCR will conduct as it is forward biased. The output voltage $V_0 = (V_s/R)$ will have same wave shape as that of source V_s . Load current i_0 will be in phase with the load voltage v_0 , hence i_0 will have wave shape similar to load voltage v_0 & v_s .
- At $\omega t = \pi$, source voltage $v_s = 0$, load voltage $v_0 = 0$ and load current $i_0 = 0$. Therefore, the current through the SCR becomes zero at this instant and it is reversed biased from $\omega t = \pi$ to 2π .

1.7 Voltage and Current ratings of SCR:

- ☐ The thyristor rating indicate voltage, current, power and temperature limits within which a thyristor can be used without damage.
- ☐ For reliable operation of a thyristor it should be ensured that its current & voltage rating are not enhanced during its working.
- ☐ If a thyristor handles voltage, current & power greater than its specified rating, the junction temperature may rise above the safe limit as a result the thyristor may get damaged therefore to an SCR are selected the rating of that SCR should not exceed their normal working voltage.
- ☐ A thyristor has several ratings such as voltage, current power, dv/dt , di/dt , turn on time, turn off time etc.

Anode Voltage Rating

- ☐ A thyristor is made up of several layers. The middle junction j_2 blocks the forward voltage whereas the two-end junction j_1 & j_3 blocks the reverse voltage.
- ☐ The anode voltage rating indicates the value of maximum voltage that a thyristor can withstand with the breakdown of the junctions as with gets circuit open.

Anode current rating

- ☐ A thyristor is made up of semiconductor material, so its normal capacity is very small.
- ☐ At high anode current the junction temperature may exceed the rated value so the device may be damaged.
- ☐ As the junction temperature is dependent on the current handled by the thyristor, a current choice of current rating is essential for long working life of the device.

1.8 Protection of SCR:

For reliable operation of thyristor protection technique is needed for thyristor.

- 1) Over voltage protection
- 2) Over current protection
- 3) Gate protection
- 4) dv/dt Protection
- 5) di/dt protection

1.8.1 Over voltage protection

Over voltage transients are perhaps the main cause of thyristor failure. Transient over voltages cause false operation of the circuit by unwanted turn on of a thyristor or permanent damage to the device due to reverse break down.

A thyristor may be subjected to internal or external over voltage. The internal over voltage is caused by the thyristor operation whereas the external over voltage comes from the supply lines or the load circuit.

1. Internal over voltage

Large voltage may be generated internally during the commutation of thyristor after thyristor anode current reduces to zero, anode current reverse due to stored charges, this causes internal over voltage due to this internal over voltage the thyristor may be destroyed permanently.

2. External over voltage

External over voltage are caused due to interference or short circuit of the supply and also due to lightning strokes on the lines feeding the thyristor. Over voltage may damage the thyristor by inverse breakdown for reliable operation over voltage must be suppressed by adopting suitable technique.

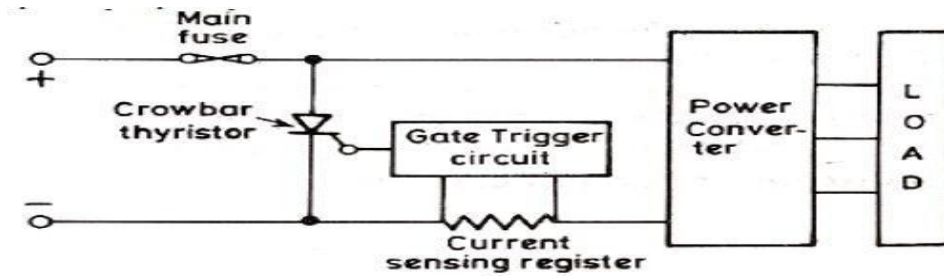
Suppression of over voltage

In order to keep the protective component to a minimum thyristors are chosen with their peak voltage rating of 2.5 to 3 times of their normal peak working voltage. The effect of over voltage is usually minimized by using RC circuit and nonlinear resistors called voltage clamping devices.

1.8.2 Over Current protection

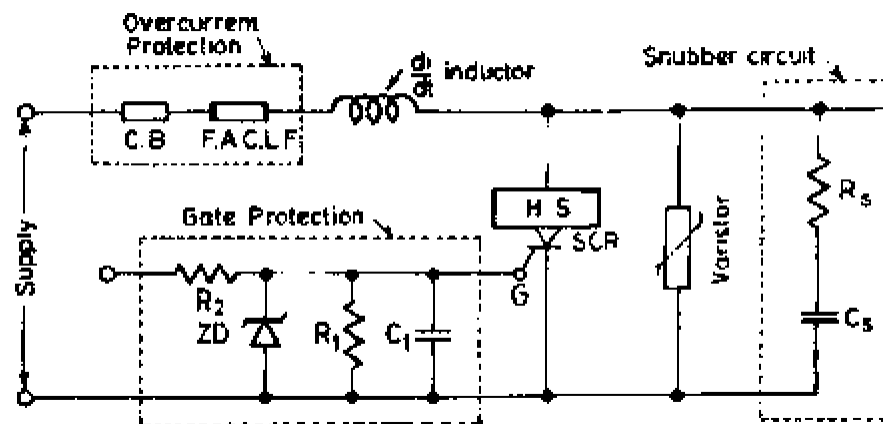
- Thyristor is subjected to over current due to fault short circuit or surge currents due to this over current junction temperature may exceed the rated value and the device may be damaged thus there is a need for the over current protection of SCR.
- Over current protection in thyristor circuit achieved through the use of circuit breakers & fast acting current limiting fuse (FACLF)

Electric crowbar protection



A thyristor possess high surge current capability, it can be used in an electronic crowbar circuit for over current protection of power converters using SCR. An electronic crowbar protection provide rapid isolation of the power converter before any damage occurs. The circuit for electronic crowbar protection circuit is shown above.

1.8.3 Gate protection :



- The Gate circuit should be protected from over voltages and over currents.
- Over voltages in the gate circuit can cause false triggering and over current can cause high junction temperature.
- Over voltages thyristor protection is achieved by using a Zener diode and a resistor can be used to protect the gate circuit from over current.
- Noise in gate circuit can also cause false triggering which can be avoided by using a resistor R_1 and a capacitor C_1 in parallel.
- A diode (D) may be connected in series or in parallel with the gate to protect it from high reverse voltage.

dv/dt Protection :

- If rate of rise of suddenly applied voltage across the thyristor is high the device may get turned on with absence of gate signal such phenomenon of turning ON a thyristor is called dv/dt triggering.
- It must be avoided which can be achieved by using Snubber circuit in parallel with the device.

1.9.Firing Circuits:

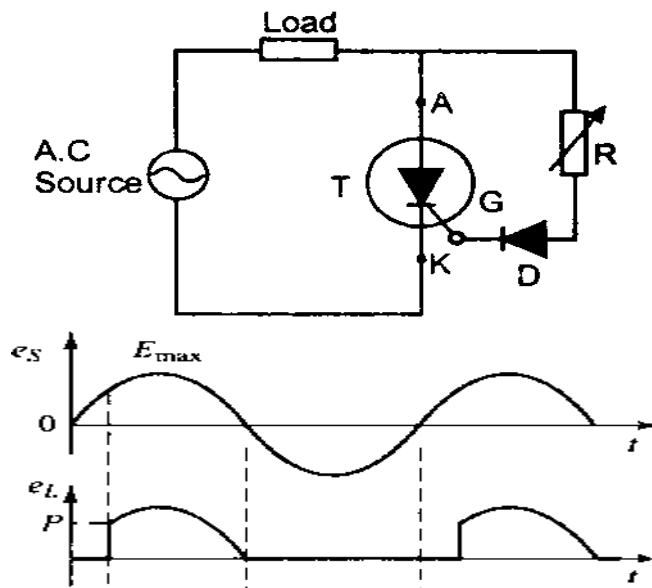
1.9.1 General layout diagram of firing circuit

The different firing circuits used in SCR are

- ☐ R-firing circuit
- ☐ RC-firing circuit
- ☐ UJT pulse trigger circuit
- ☐ Synchronous triggering (Ramp Triggering) circuit

1.9.2 R firing circuits or Resistance triggering circuit

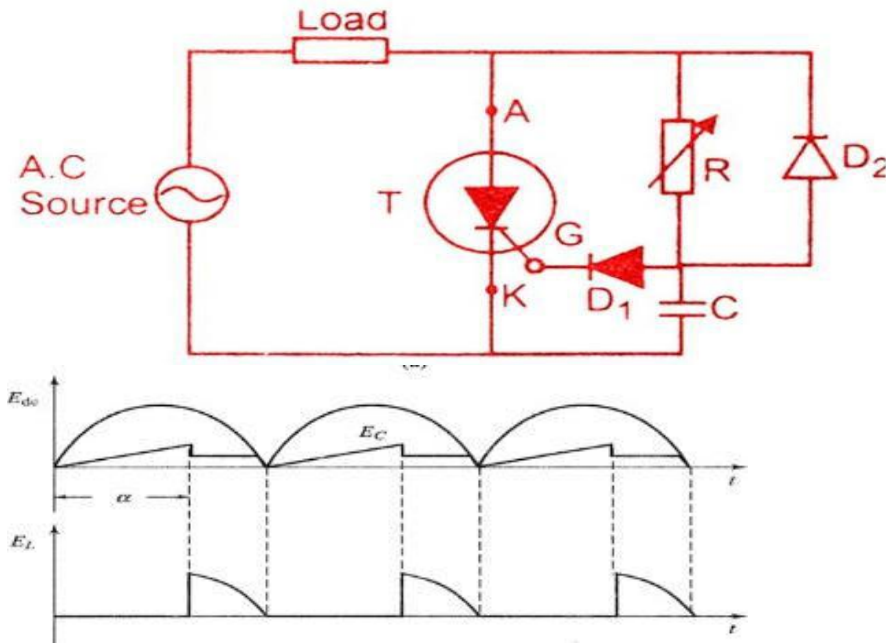
- ☐ The circuit diagram and waveform of resistance triggering is shown below.



- ☐ In this method, the variable resistance R is used to control the gate current.
- ☐ Depending upon the value of R, when the magnitude of the gate current reaches the latching current of the device the SCR starts to conduct.
- ☐ The diode D is called as blocking diode. It prevents the gate cathode junction from getting damaged in the negative half cycle.
- ☐ By considering that the gate circuit is purely resistive, the gate current is in phase with the applied voltage.
- ☐ By using this method we can achieve maximum firing angle up to 90° .

1.9.3 R-C firing circuit

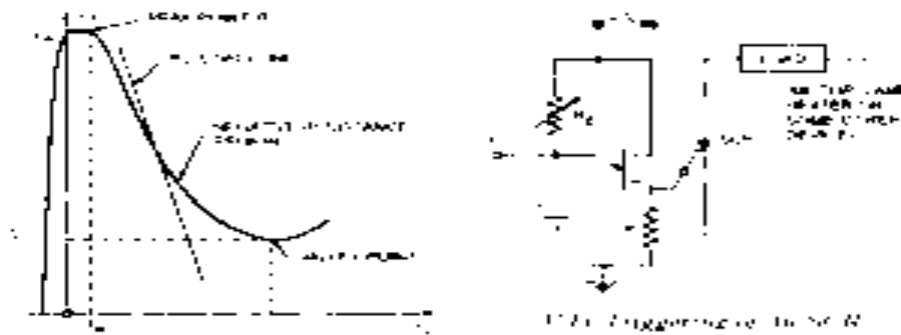
□ The circuit diagram and waveform of resistance-Capacitance triggering is shown below.



- By using this method we can achieve the firing angle more than 90°.
- In the positive half cycle, the capacitor is charged through the variable resistance R up to the peak value of the applied voltage.
- The variable resistor R controls the charging time of the capacitor.
- Depends upon the voltage across the capacitor, when sufficient amount of gate current will flow in the circuit, the SCR starts to conduct.
- In the negative half cycle, the capacitor C is charged up to the negative peak value through the diode D₂.
- Diode D₁ is used to prevent the reverse break down of the gate cathode junction in the negative half cycle.

1.9.4.UJT pulse trigger circuit

- The circuit diagram and waveform of UJT pulse triggering is shown below



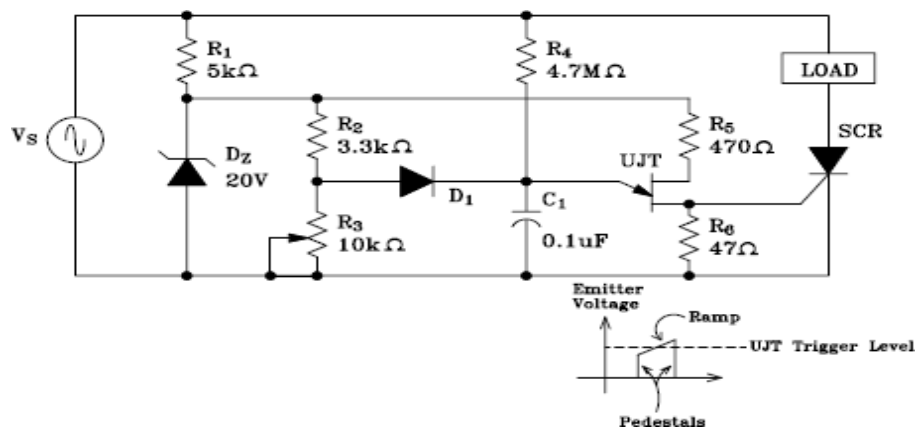
- ❑ One common application of the Uni-junction transistor is the triggering of the other devices such as the SCR, triac etc.
- ❑ The basic elements of such a triggering circuit are shown in figure. The resistor R_E is chosen so that the load line determined by R_E passes through the device characteristic in the negative resistance region, that is, to the right of the peak point but to the left of the valley point, as shown in figure.
- ❑ If the load line does not pass to the right of the peak point P, the device cannot turn on.
- ❑ For ensuring turn-on of UJT $R_E < V_{BB} - V_p / I_p$
- ❑ This can be established as below
- ❑ Consider the peak point at which $I_{RE} = I_p$ and $V_E = V_p$
- ❑ The capacitor C determines the time interval between triggering pulses and the time duration of each pulse.
- ❑ By varying R_E , we can change the time constant $R_E C$ and alter the point at which the UJT fires.

This allows us to control the conduction angle of the SCR, which means the control of load current.

1.9.5 Synchronous triggering (Ramp Triggering)

- The circuit, shown below, uses a UJT to trigger a SCR.
- The UJT is used to more accurately trigger the SCR. When the source voltage exceeds 20V, the Zener diode (D_Z) will begin to conduct, applying a DC voltage across the base connections of the UJT.
- At the same time, diode D_1 will be forward biased, and the capacitor will quickly charge through R_1 and R_2 .
- Once the capacitor charges to the voltage across R_3 , D_1 will become reverse biased and the

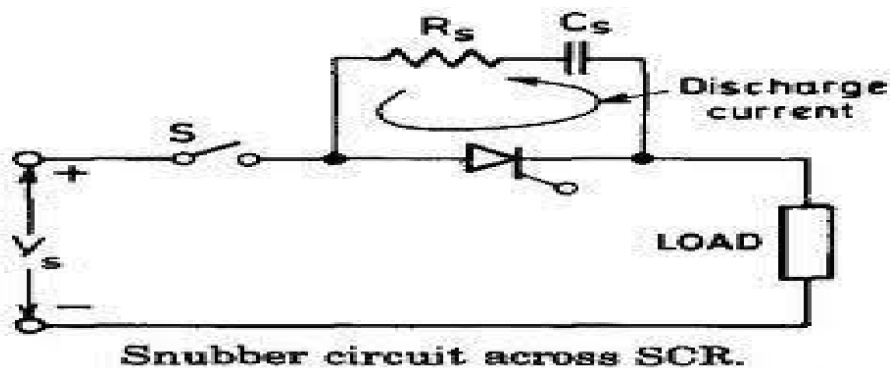
capacitor will continue to slowly charge through R_4 . This represents the ramp portion of the emitter voltage.



The capacitor continues to charge until the UJT fires. At this point the capacitor will quickly discharge through R_6 .

- The capacitor discharge is sufficient to trigger the SCR. The point at which the UJT fires can be adjusted by varying the pot R_3 . With a large setting on R_3 , the capacitor must charge to a larger value before D_1 becomes reverse biased.
- This causes the UJT to fire faster, resulting in more of the source voltage appearing across the SCR.

1.10 Design of Snubber Circuits:



- It consists of a capacitor C_s connected in series with a resistor R_s which is applied parallel with the thyristor.
- when S is closed then voltage V_s is applied across the device C_s behaves like a shortcircuit. Therefore voltage across the device is zero.

- Gradually voltage across C_s builds up at a slow rate so dv/dt across the thyristor will stay in specified range.
- Before turning on of thyristor, C_s is fully charged and after turning on of thyristor it discharges through the SCR.
- This discharging current can be limited with the help of a resistance (R_s) connected in series with the capacitor (C_s) to keep the value of current and rate of change of current in a safe limit.

di/dt Protection :

- When a thyristor is turned on by gate pulse then charge carriers spread through its junction rapidly.
- If the rate of rise of anode current, i.e. di/dt is greater than the spreading of charge carriers then localized heat generation will take place which is known as local hot spots. This may damage the thyristor.
- To avoid local hot spots we use an inductor in series with the device as it prevents high rate of change of current through it.

1.1.Construction, Operation, V-I characteristics & application of IGBT

This device combines into it the advantages of both MOSFET and BJT. So an IGBT has high input impedance like a MOSFET and low-on-state power loss as in a BJT

BASIC STRUCTURE:

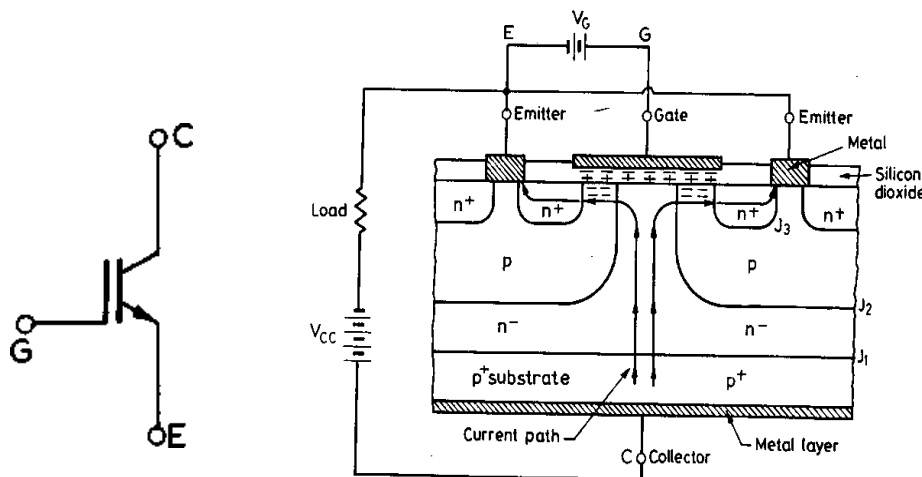


Fig1(a) Symbol of IGBT (b) Basic structure of an insulated gate bipolar transistor (IGBT).

- It has four layers that are P^+ , n^- , P , n^+ , three junctions such as J_1 - Pn^+ , J_2 - Pn^- , J_3 - P^+n^- . and three terminal such as Emitter, Collector, Gate .
- It is constructed virtually in the same manner as a power MOSFET.
- There is, however, a major difference in the substrate. The n^+ layer substrate at the drain in a power MOSFET is now substituted in the IGBT by a p^+ layer substrate

called collector.

- Like a power MOSFET, an IGBT has also thousands of basic structure cells connected appropriately on a single chip of silicon.

OOPERATION:

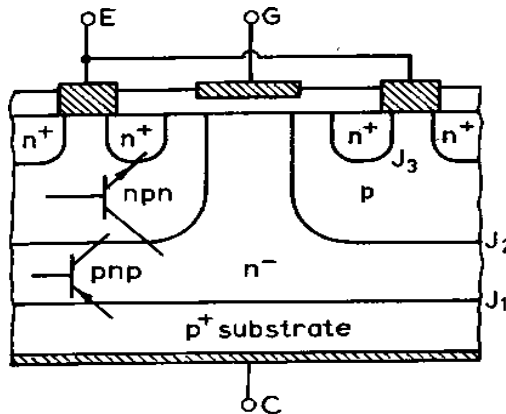


FIG :2(a) Basic structure

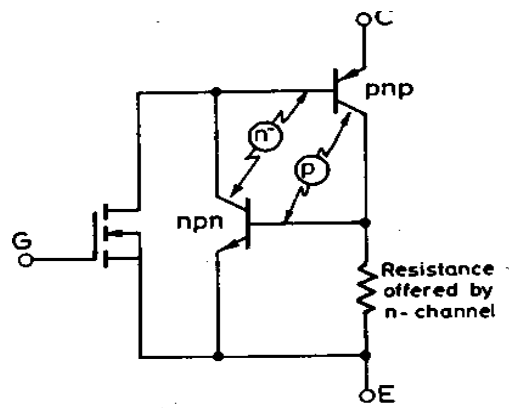


Fig2(b) Its equivalent Circuit

It shows three modes of operations such as

- Reverse blocking mode.
- Forward blocking mode
- Forward conduction mode.

I.Reverse blocking mode.

When a negative voltage applied to the collector of the IGBT then the junction J₃ behaves as reverse biased so current conduction in it is not possible this condition is called as reverse blocking mode.

II.Forward blocking mode.

When a positive voltage is applied to the collector of IGBT, gate to collector shortcircuits, junction J₃ is forward biased but junction J₂ is reverse biased so current conduction is not possible this condition is called as forward blocking mode.

III.Forward conduction mode.

When a positive voltage is applied to the collector and a positive gate to emitter is applied in IGBT then junction J₃ is forward biased and an inversion layer or n-channel is created near the junction J₁ inside the P-region thus the IGBT behaves as a PN Junction with gate control so current conduction is possible in it from collector to emitter through collector, P⁺ substrate, N⁻, N channel in p, N⁺, emitter.

V-I CHARACTERISTICS:

Though IGBT behaves as a PN junction diode in forward conduction mode so its V-I characteristics is same as PN junction . in IGBT the gate control is main advantage.

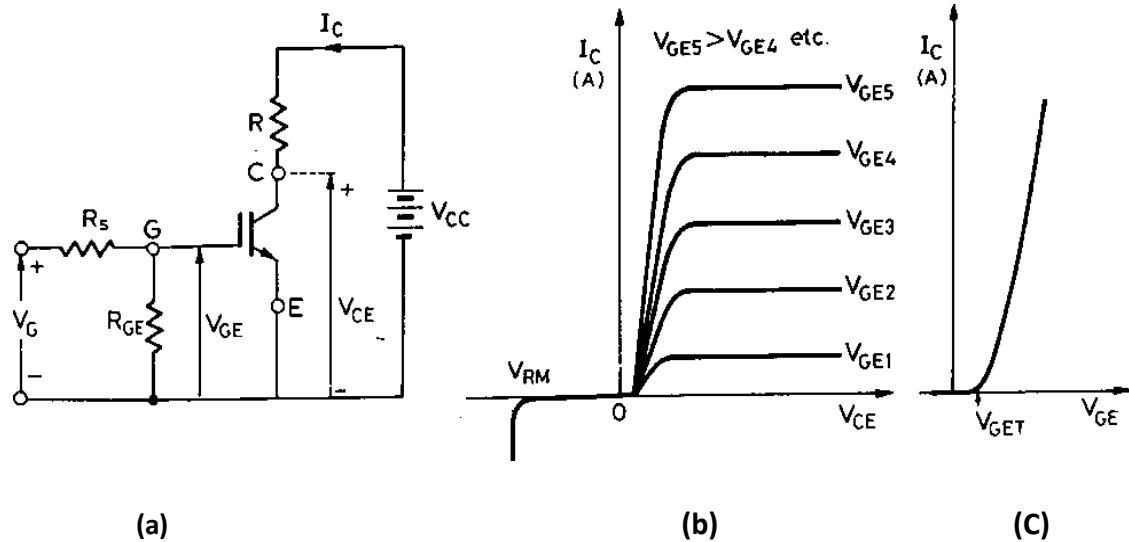


Fig 3(a) Circuit Diagram

(b) Static V-I characteristics

(c) Transfer Characteristics

APPLICATION OF IGBT:

IGBTs are used in various applications such as

- AC and DC motor drives,
- Unregulated Power Supply (UPS),
- Switch Mode Power Supplies (SMPS),
- traction motor control and induction heating,
- inverters

1.1.Construction, Operation, V-I characteristics & application of MOSFET:

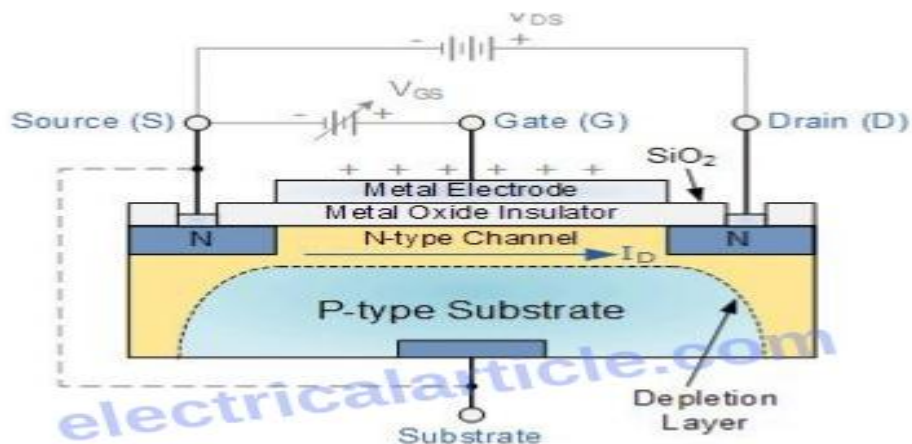
Metal Oxide Silicon Field Effect Transistors commonly known as MOSFETs are electronic devices used to switch or amplify voltages in circuits. It is a current controlled device and is constructed by three terminals. MOSFET has four terminals called Drain (D), Source (S), Gate (G), and Substrate (SS).

There are two types of MOSFET, which are listed below:

1. Depletion Type MOSFET
2. Enhancement Type MOSFET

Construction of MOSFET

Power MOSFET has a vertically oriented four-layer structure. The p-type middle layer term as the body. The n^- layer is the drift layer. This layer is lightly doped as compared to the drain and source layer. The breakdown voltage of power MOSFET determines from the width of the drift layer. First and last both layers are an n^+ layer. First layer is the source layer and the last layer is the drain layer.



The gate terminal is not directly connected with p-type, there is an oxide layer between the metal and semiconductor. This oxide layer act as a dielectric layer between the metal and the semiconductor.

Operating principle of MOSFET

The operation of MOSFET divides into two parts

1. Formation of the depletion layer
2. Creation of Inversion Layer

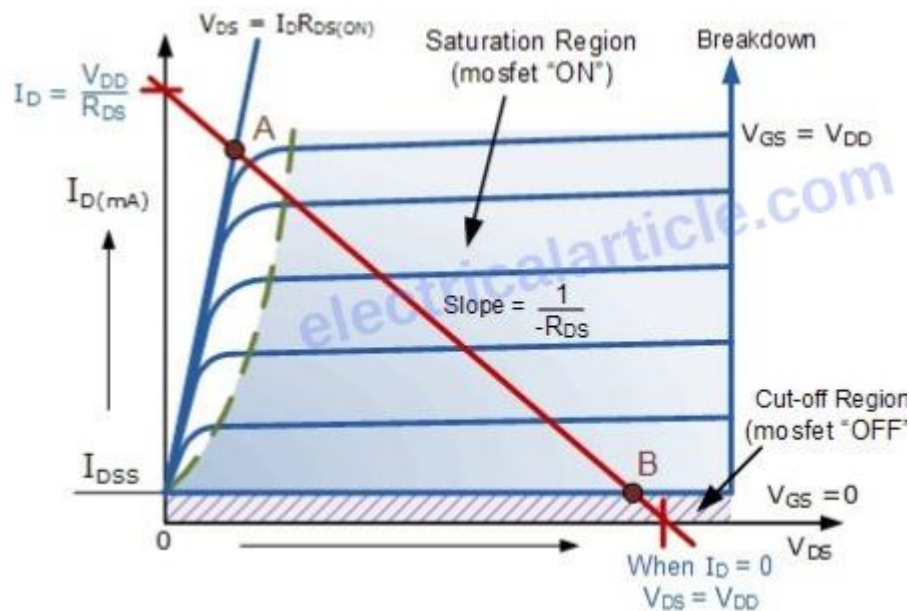
1) Formation of the depletion layer

By connecting a positive voltage to the drain with respect to the source and the gate is positive with respect to the body, the MOSFET works as forward biased. The p-layer has a large number of holes and few electrons. The holes are the majority charge carrier and electrons are minority charge carrier. Due to the positive voltage applied between the gate and the body, these electrons are attracted towards the gate and gather below the oxide layer and produce the depletion layer.

2) Creation of Inversion Layer

The number of electrons below the oxide layer will be greater than the number of holes if the positive gate voltage increases further. Hence, n-type of sublayer forms below the oxide layer. This process is known as the creation of the inversion layer.

I-V characteristic



MOSFET applications

- Radiofrequency applications use MOSFET amplifiers extensively.
- MOSFET behaves as a passive circuit element.
- Power MOSFETs can be used to regulate DC motors.
- MOSFETs are used in the design of the chopper circuit.

Advantages of MOSFET

- MOSFETs operate at greater efficiency at lower voltages.
- Absence of gate current results in high input impedance producing high switching speed.

Disadvantages of MOSFET

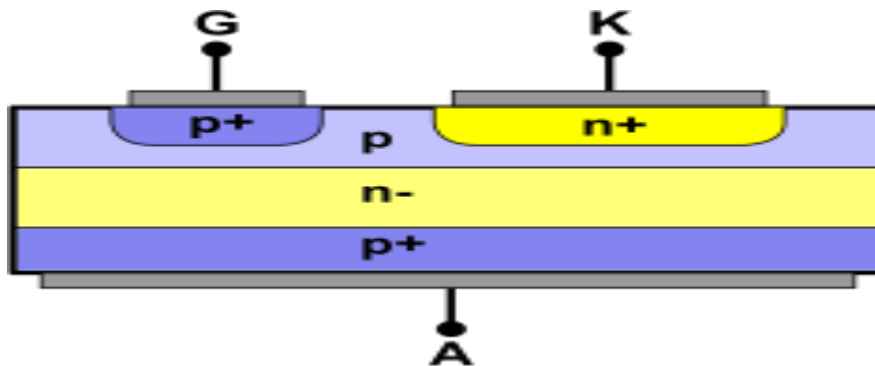
- MOSFETs are vulnerable to damage by electrostatic charges due to the thin oxide layer.
- Overload voltages make MOSFETs unstable.

1.1.Construction, Operation, V-I characteristics & application of GTO

DIAC,TRIAC:

1.1 GTO (Gate turn-off Thyristor)

- A gate turn off thyristor is a pnpn device. In which it can be turned ON like an ordinary SCR by a positive gate current. However it can be easily turned off by a negative gate pulse of appropriate magnitude.



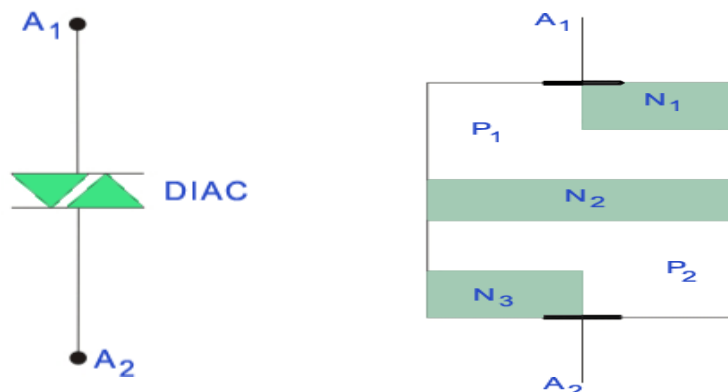
- Conventional SCR are turned on by a positive gate signal but once the SCR is turned on gate loses control over it. So to turn it off we require external commutation circuit. These commutation circuits are bulky and costly. So due to these drawbacks GTO comes into existence.

The salient features of GTO are:

- GTO turned on like conventional SCR and is turned off by a negative gate signal of sufficient magnitude.
- It is a non-latching device.
- GTO reduces acoustic and electromagnetic noise. It has high switching frequency and efficiency.
- A gate turn off thyristor can turn on like an ordinary thyristor but it is turned off by a negative gate pulse of appropriate magnitude.
- The negative gate current required to turn off a GTO is quite large that is 20% to 30 % of anode current.
- It is compact and cost less.

1.1.THE DIAC

- A DIAC is a device which has two electrodes, two terminals and four layers and it is a member of the thyristor family.
- DIACs are used in the triggering of thyristors.
- The figure below shows a symbol of a DIAC, which resembles the connection of two diodes in series.

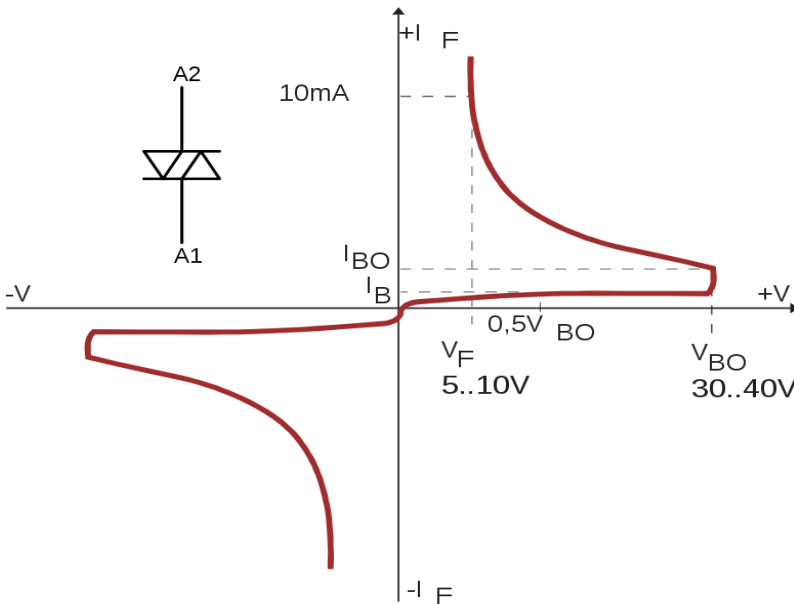


- ☐ DIACs have no gate electrode, unlike some other thyristors that they are commonly used to trigger, such as a TRIAC.
- ☐ DIAC=DIODE+AC
- ☐ The advantage of a DIAC is that it can be turned on or off simply by reducing the voltage level below its avalanche breakdown voltage.

DIAC Characteristics

- ☐ From the figure above, we can see that a DIAC has two p-type material and three n-type materials also, it does not have any gate terminal in it.
- ☐ The DIAC can be turned on for both the polarity of voltages.
- ☐ When A_2 is more positive with respect to A_1 then the current does not flow through the corresponding N-layer but flows from P_2 - N_2 - P_1 - N_1 .
- ☐ When A_1 is more positive A_2 then the current flows through P_1 - N_2 - P_2 - N_3 .
- ☐ When the applied voltage is small in either polarity, a very small current flows which is known as leakage current because of the drift of electrons and holes in the depletion region.
- ☐ Although a small current flows, it is not sufficient to produce avalanche breakdown, hence the device remains in the non-conducting state.

- When the applied voltage in either polarity exceeds the breakdown voltage, DIAC current rises and the device conducts in accordance with its V-I characteristics.



Application of DIAC

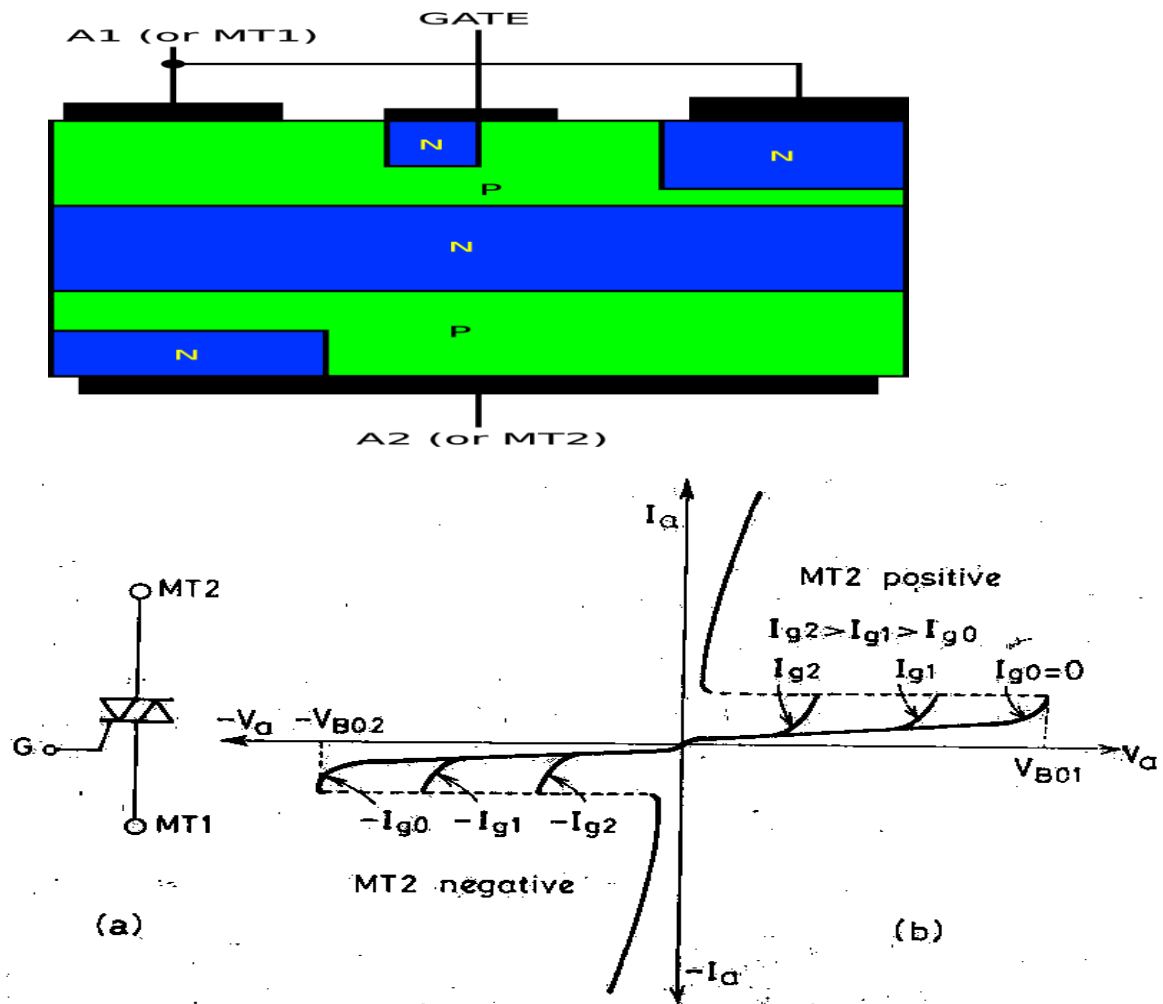
- It is its use in a TRIAC triggering circuit.
- The DIAC is connected to the gate terminal of the TRIAC.
- It can be used in the lamp dimmer circuit.
- It is used in a heat control circuit.
- It is used in the speed control of a universal motor.

1.1 THE TRIAC

- As SCR is a unidirectional device, the conduction is from anode to cathode and not from cathode to anode. It conducts in both direction. It is a bidirectional SCR with three terminal.

$$\text{TRIAC} = \text{TRIODE} + \text{AC}$$

- Here it is considered to be two SCRS connected in anti-parallel. As it conducts in both direction so it is named as MT_1, MT_2 and gate G.



SALIENT FEATURES

- ☐ Bidirectional triode thyristor.
- ☐ TRIAC means triode that works on ac.
- ☐ It conducts in both directions.
- ☐ It is a controlled device.
- ☐ Its operation is similar to two devices connected in anti-parallel with common gate connection.
- ☐ It has 3 terminals MT1, MT2 and gate G.

SHORT QUESTIONS WITH ANSWERS.

1. Define latching current. [W-17,19, S-19]

Ans- It is the minimum value of anode current which is most attain during turn on process to maintain the conduction when the gate signal is removed.

2. Define holding current. [W-16, S-19]

➤ **Ans-** It is the minimum value of anode current below which it must fall turning off thyristor.

3. What are the mode of operations of an SCR ? [W-10]

Ans- The SCR have 3 modes of operation:

1. Reverse blocking mode
2. Forward blocking mode(off-state)
3. Forward conduction mode(on-state)

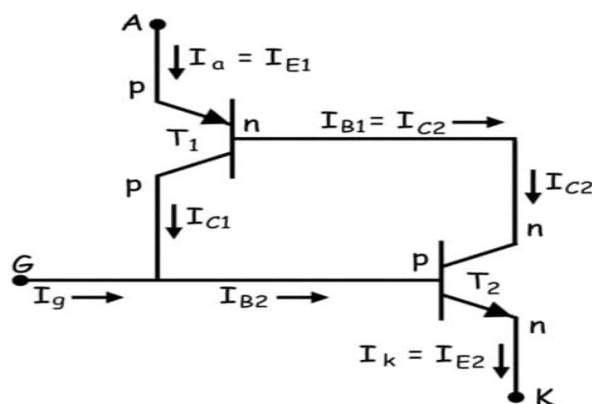
4. Write down the turning on method of SCR. [W-2009,14,16,17]

Ans- There are five methods are adopted to turn on the SCR that are:-

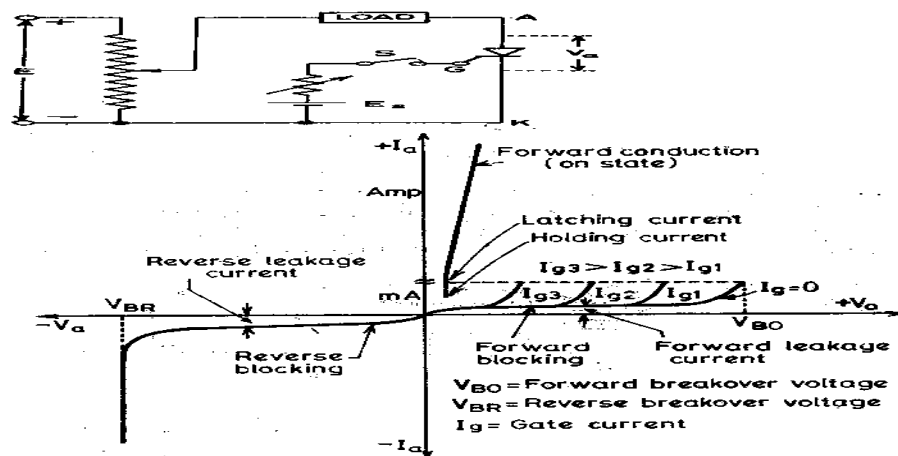
1. Forward voltage triggering
2. Gate triggering
3. $\frac{dv}{dt}$ triggering
4. Light triggering
5. Temperature triggering

6. Draw the model of Two transistor analogy of SCR. [W-11]

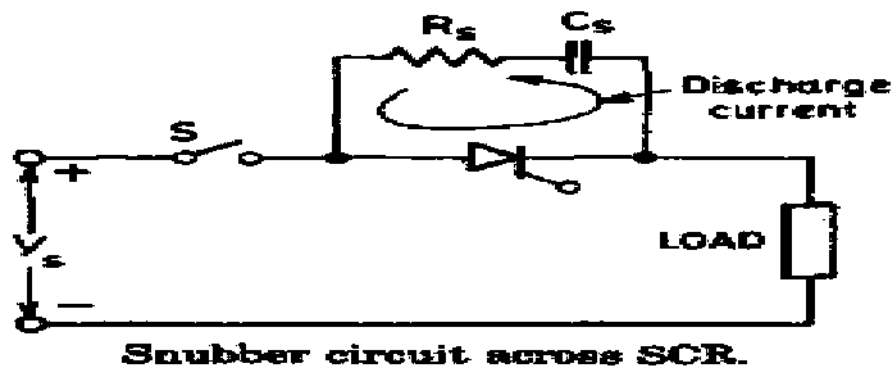
Ans-



7. Draw the V-I characteristics of SCR. [W-19]



8. Draw the snubber circuit to protect SCR. [W-20]



Long Questions.

1. Explain V-I characteristics of SCR. [W-17]
2. What are the triggering scheme seen in SCR?
3. Write a short-note on DIAC.
4. Explain turn-on method of SCR. [W-16,18, S-19, W-20]
5. Describe any two turn-off method of SCR. [W-10, 16]
6. Draw the Dynamic characteristics of SCR. Explain in detail.
7. Explain gate protection and over voltage protection of SCR.
8. Write a short-note on TRIAC.
9. Describe briefly about Snubber circuit and its essential. [W-19]
10. Briefly describe about two transistor model of SCR. [W-19, 20]

CHAPTER-2

UNDERSTAND THE WORKING OF CONVERTERS, AC REGULATORS AND CHOPPERS.

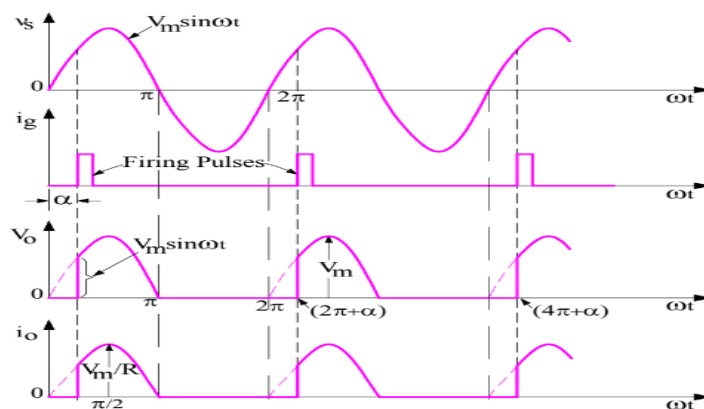
Learning Objectives:

- 2.1 Controlled rectifiers Techniques(Phase Angle, Extinction Angle control), Single quadrant semi converter, two quadrant full converter and dual Converter
- 2.2 Working of single-phase half wave controlled converter with Resistive and R-L loads.
- 2.3 Understand need of freewheeling diode.
- 2.4 Working of single phase fully controlled converter with resistive and R- L loads.
- 2.5 Working of three-phase half wave controlled converter with Resistive load
- 2.6 Working of three phase fully controlled converter with resistive load.
- 2.7 Working of single phase AC regulator.
- 2.8 Working principle of step up & step down chopper.
- 2.9 Control modes of chopper
- 2.10 Operation of chopper in all four quadrants.

2.1: Controlled rectifiers Techniques(Phase Angle, Extinction Angle control)

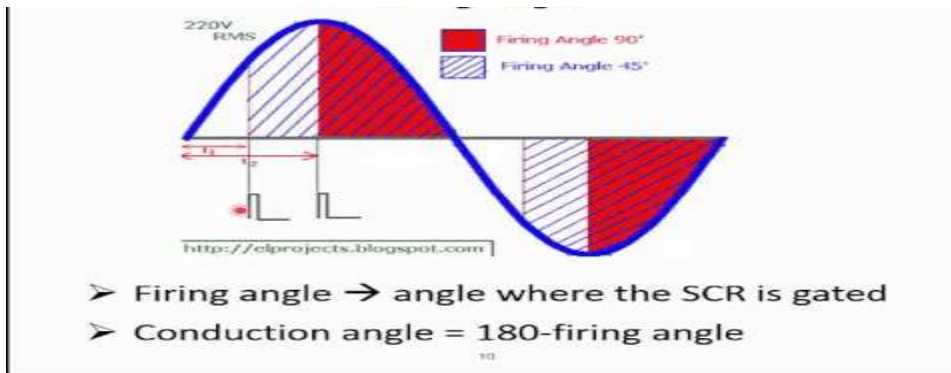
1.PHASE ANGLE CONTROL :

- In ac circuit the SCR can be turned on by the gate at any angle with respect to the applied voltage.
- The firing angle is denoted by α , $\alpha=0$
- If then the rectifier behaves as an uncontrolled rectifier, by varying the firing angle (α) we can control the turning on process of SCR which is known as phase angle control.
- The wave form of half wave controlled rectifier using phase angle control method is shown below.



2. EXTINCTION ANGLE CONTROL:

- The wave form for extinction angle control is shown below.



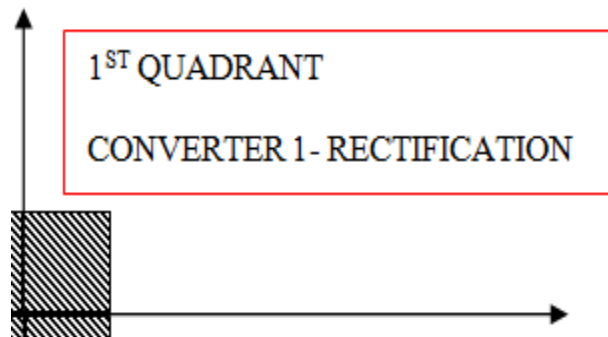
- Extinction angle is denoted by β .
- By connecting β we can also get output dc voltage which is controlled in falling edge or falling size.

2.1 Single quadrant semi converter, two quadrant full converter and dual Converter:

- According to operational point of view rectifier or converter operations are of three types.
 1. Single Quadrant Operation.
 2. Two Quadrant Operation./two quadrant full converter.
 3. Four Quadrant Operation. / dual converter.

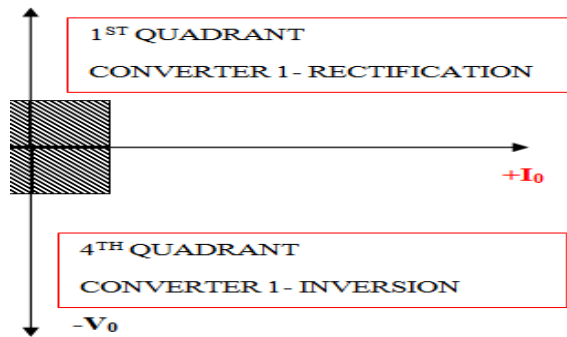
1. SINGLE QUADRANT OPERATION:-

- A half controlled converter or semi converter is an one quadrant or single quadrant converter i.e the output voltage and current have one polarity or single polarity.
- The symbolic diagram of half controlled semi converter and its first quadrant operation is shown below.



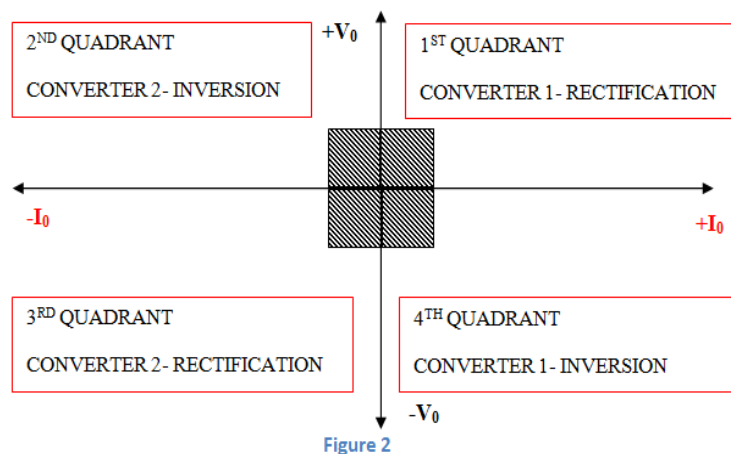
2. TWO QUADRANT OPERATION:-

- In two quadrant full converter the voltage polarity can reverse but current direction can't reverse.
- The symbolic diagram and quadrant operation is shown below.



3.FOUR QUADRANT OPERATION:-

- In four quadrant dual converter both voltage and current polarity can be reversed.
- Four quadrant converter can be obtained by connecting two quadrant converter back to back.
- The symbolic diagram & quadrant operation is shown below

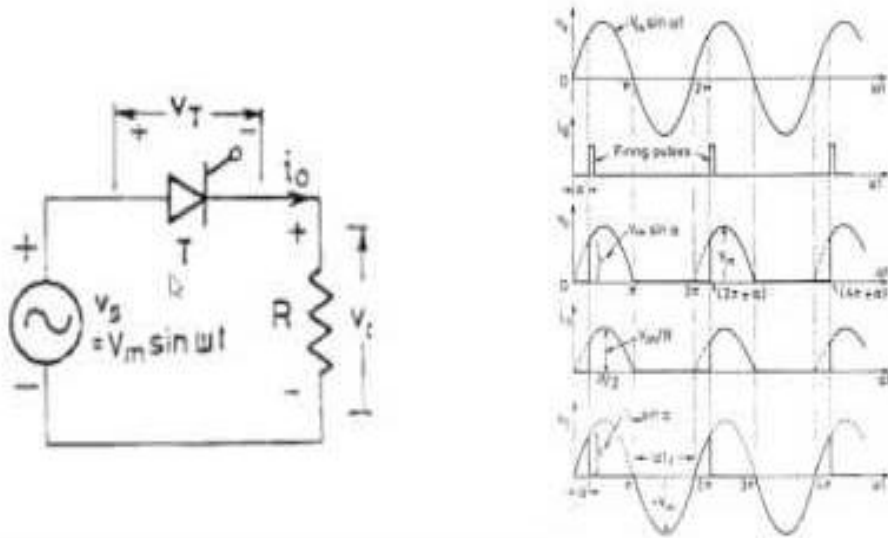


CONVERTERS/ RECTIFIERS :

- Rectification is a process of converting alternating current or voltage into direct current or voltage.
- Rectifier is a converter which converts alternating current or voltage into direct current or voltage.
- Rectifier circuit can be classified into three types
 - I. Uncontrolled Rectifier.
 - II. Fully controlled Rectifier.
 - III. Half controlled or Semi controlled Rectifier.
- Diodes are used in uncontrolled rectifier for rectification where as thyristors are used in fully controlled rectifier and half control rectifier contains mixture of diodes & thyristors.
- Half controlled rectifier is otherwise known as semi converter and fully controlled rectifier is known as full converter.

2.2 Working of single-phase half wave controlled converter with Resistive load.

- The circuit diagram and wave form of single phase half wave controlled rectifier with R-load is shown below.fig

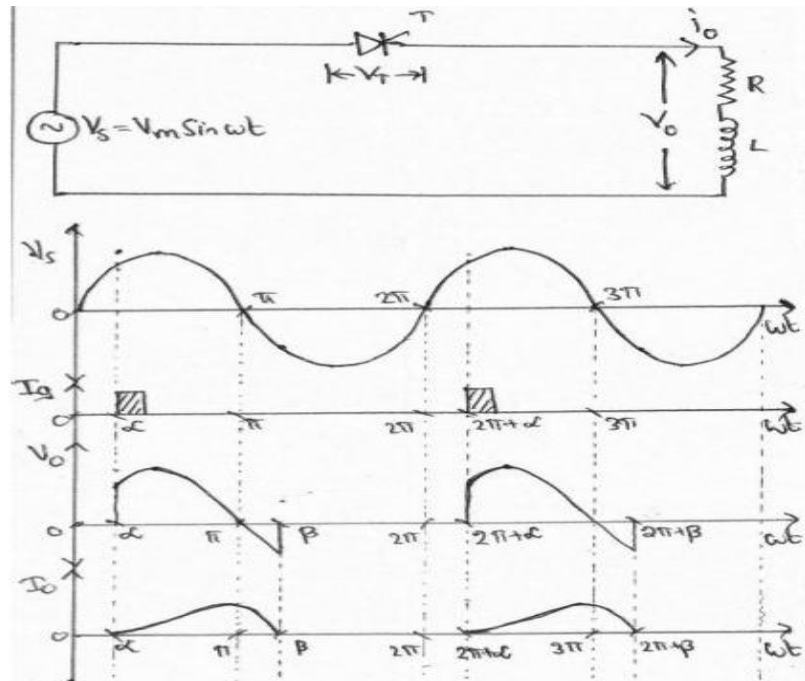


- During the positive half cycle of the ac supply anode is positive and cathode is negative so the thyristor is forward biased at that instant. $V_T=0$ it follows the input voltage. $V_o=0, I_o=0$
- At $\omega t = \alpha$ the thyristor is triggered so it starts conducting at that instant, at that instant $V_T=0$ it follows the input voltage, I_o it follows the input voltage.
- During negative half cycle anode is negative and cathode is positive so the thyristor is reverse biased, at that instant V_T follows the input voltage. $V_o=0, I_o=0$
- So in reverse biased condition as the output current is zero so the thyristor gets turned off.
- The output voltage and current equation is

$$\begin{aligned}
 \therefore V_o(Avg) &= \frac{1}{2\pi} \int_0^{2\pi} V_m \sin(\omega t) d\omega t \\
 &= \frac{V_m}{2\pi} [-\cos \omega t]_{\alpha}^{\pi} \\
 &= \frac{V_m}{2\pi} (1 + \cos \alpha)
 \end{aligned}$$

2.2 Working of single-phase half wave controlled converter with R-L load.

- The circuit diagram and wave form of single phase half wave rectifier with R-L load is shown below.

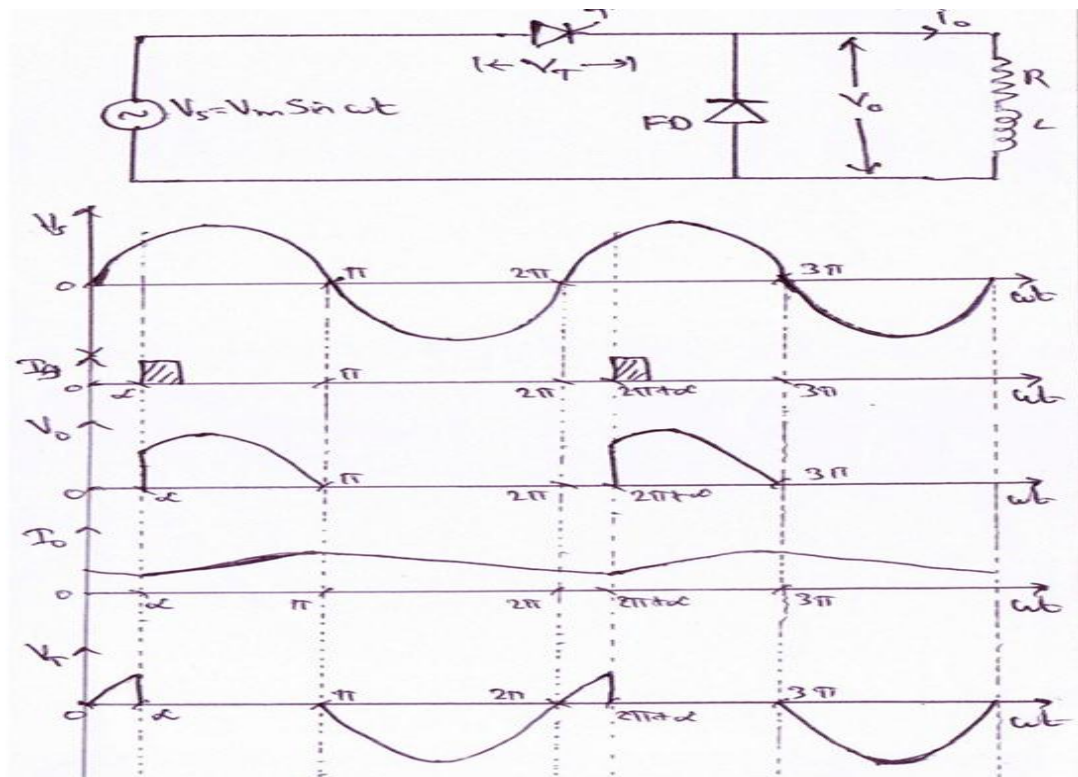


- In the given figure the input voltage is $V_s = V_m \sin(\omega t)$
 V_T = Voltage across the thyristor.
 V_o = Output voltage of thyristor
 I_T = current through the thyristor
 I_o = output current or load current.
- In the positive half cycle of the ac supply anode is positive and cathode is negative so the thyristor is forward biased at that instant .
 $V_T = V_s$ and follows the input voltage or supply voltage.
 $V_o = 0, I_o = 0$
- At $\omega t = \alpha$, the thyristor is fired so it starts conducting at that instant , $V_o = V_s, V_T = 0$,
 I_o = rises to its maximum point.
- During negative half cycle, at $\omega t = \pi$ anode is negative and cathode is positive so the thyristor is said to be reverse biased but not turned off because excess of charge carriers stored in the inductor so at that instant
 V_o = follows the input voltage up to β .
 V_T = it follows the input voltage from β ,
 I_o = decreases in the positive half cycle.

- When the current through the load decreases and reaches to zero or below the holding current of the thyristor at that instant the thyristor is turned off so at that condition
 $V_T = V_s$ It follows the input voltage
 $V_o = 0$,
 $I_o = 0$

2.2 Working of single-phase half wave controlled converter R-L load with Freewheeling Diode.

- The circuit diagram and wave form of single phase half wave rectifier with R-L load and Freewheeling diode is shown below.



- During the positive half cycle anode is positive and cathode is negative so the thyristor is forward biased at that condition
 $V_T = V_s$ or it follows the input voltage
 $V_o = 0$
 $I_o = 0$
- At $\omega t = \alpha$, the thyristor is triggered so it starts conducting, at that instant the Freewheeling diode is reverse biased and
 $V_T = 0$
 $V_o =$ follows the input voltage V_s .
 $I_o =$ rises to its maximum point.

- During negative half cycle at $\omega t = \pi$ the anode is negative and cathode is positive so the thyristor is set to be reverse biased and gets turned off. At that time freewheeling diode is forward biased and starts conducting so the excess charge carriers stored in the inductor flows through the freewheeling diode, at that instant
 $V_o = 0$,
 $V_T = V_s$, it follows the input voltage.
 I_o = Decreases from its peak value.
- So the current through the load does not become zero as before turning off the freewheeling diode, the thyristor again starts conducting so it shows that the load current is continuous.
- The output voltage equation is

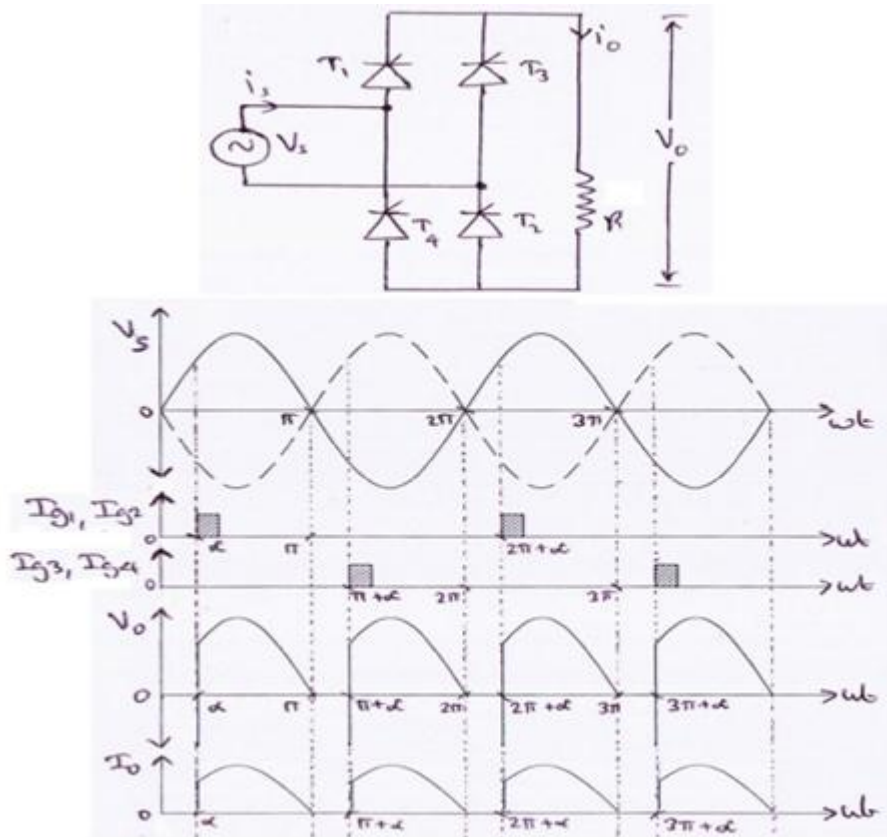
$$\begin{aligned}\therefore V_o(Avg) &= \frac{1}{2\pi} \int_0^{2\pi} V_m \sin(\omega t) d\omega t \\ &= \frac{V_m}{2\pi} [-\cos \omega t]_{\alpha}^{\pi} \\ &= \frac{V_m}{2\pi} (1 + \cos \alpha)\end{aligned}$$

2.3 : Understand need of freewheeling diode.

- The freewheeling diode is commonly describe as a commutating diode or bypass diode as its function is to commutate the load current away from the rectifier whenever the load voltage flows into reverse state.
- Freewheeling diodes are also known as kickback diode, clamp diodes, commutating diodes, suppression diodes, or snubber diode etc.
- By using freewheeling diode in R-L load, the load current graph will be improved and the output voltage curve will not be extended in reverse direction.
- It will give better performance so the efficiency will be high and the diode is also known as conducting diode.

2.4 Working of single phase full wave fully controlled converter with resistive loads:

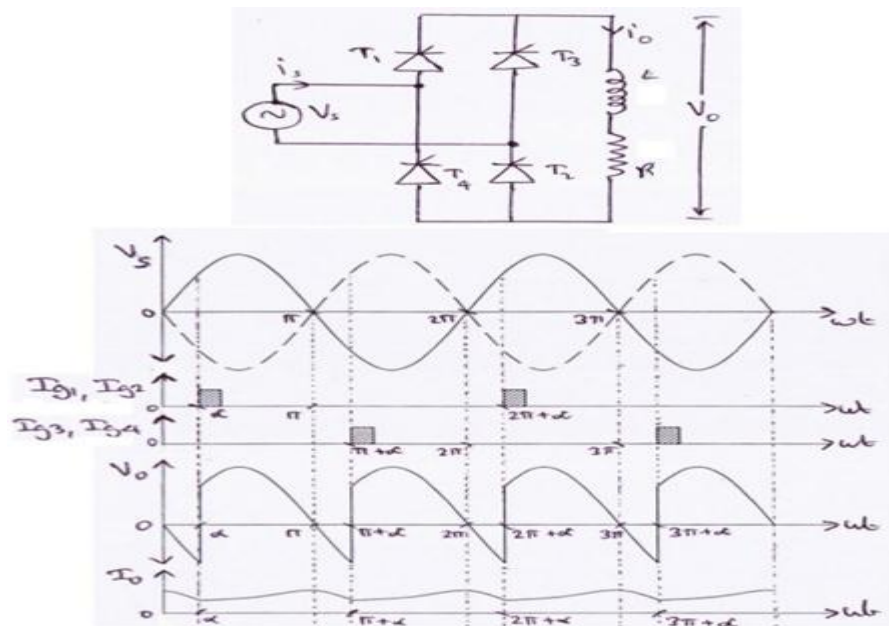
- The circuit diagram and wave form of single phase full wave converter or rectifier with R load are shown below.



- All four devices used are thyristors. The turn-on instants of these devices are dependent on the firing signals that are given.
- In this bridge circuit diagonally elements or opposite pair of thyristors made to conduct and commute simultaneously.
- In positive half cycle thyristors T_1, T_2 are forward biased and it fired at an angle α simultaneously T_1 and T_2 are conducts at that instant
 $V_o = V_s$
 $I_o = V_o/R = V_s/R$ flows through the path $V_s-T_1-R-T_2-V_s$ and T_3, T_4 are reverse biased.
- In negative half cycle of input voltage, SCR's T_3 & T_4 are forward biased and triggered at an angle of $(\pi + \alpha)$ so T_3 and T_4 are conducts at that instant output current flows through the path $V_s-T_3-R-T_4-V_s$ which is positive and the output voltage also positive and T_3 & T_4 becomes off at 2π .

2.4 Working of single phase full wave fully controlled converter with R-L loads.

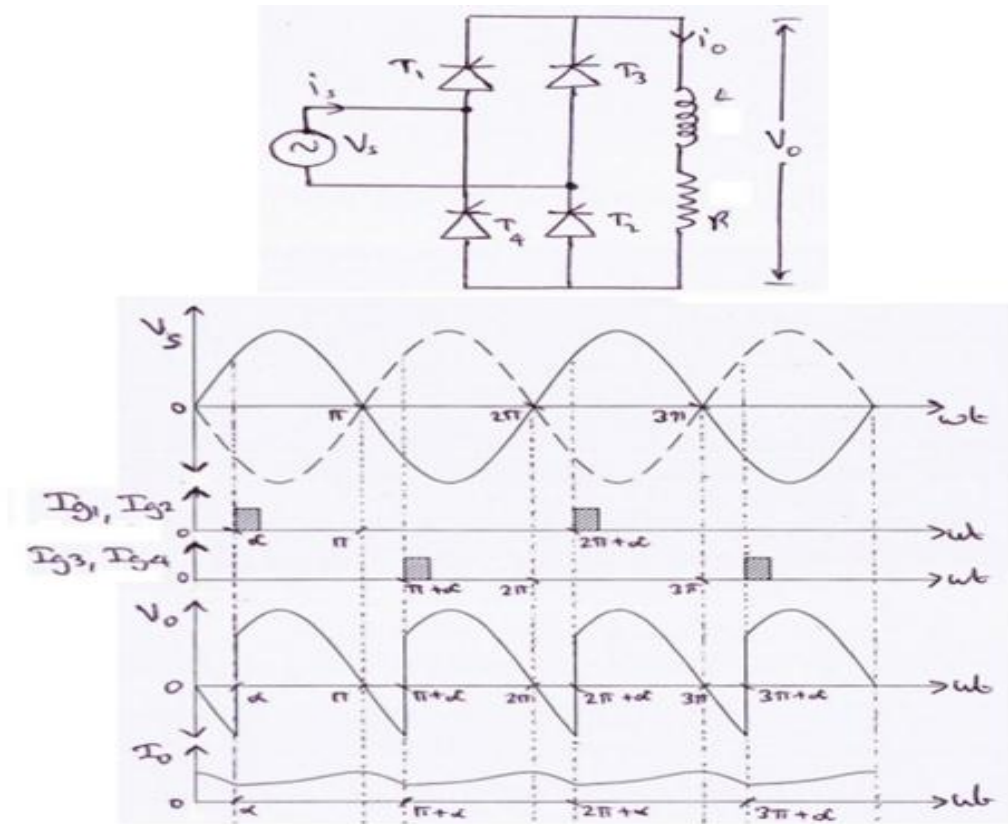
- The circuit diagram and wave form of single phase full wave fully controlled converter or rectifier with R-L load are shown below.



- The circuit consists of four thyristors T_1, T_2, T_3 and T_4 , a voltage source and a RL load.
- During the positive half cycle of the AC supply the thyristors T_1 and T_2 are forward biased but they do not conduct until a gate supply is applied to them.
- When a gate pulse is given to the thyristor T_1 and T_2 at $\omega t = \alpha$, they get turned ON and begin to conduct.
- When the thyristors T_1 and T_2 are ON, the input voltage is applied to the load but due to the inductor present in the load the current through the load builds up slowly through the path V_s - T_1 -Load- T_2 - V_s .
- During the negative half cycle, T_3 & T_4 are forward biased, the thyristor T_1 and T_2 get reverse biased but the current through them is not zero due to the inductor and they do not turn OFF.
- The current through the inductor begins to decay to zero and T_1 & T_2 conduct for a small duration in the negative half cycle.
- When a gate pulse is given to the thyristor T_3 & T_4 at $\omega t = \pi + \alpha$, they get turned ON and begin to conduct.
- When the thyristors T_3 & T_4 are ON, the load current shifts its path to T_3 & T_4 and turns off T_1 & T_2 at $\omega t = \pi + \alpha$.
- When T_3 & T_4 are ON, the current through the load builds up slowly through the path V_s - T_3 -Load- T_4 - V_s .
- The load receives voltage during both the half cycles.
- The average value of output voltage can be varied by varying the firing angle α .
- The waveform shows the plot of input voltage, output voltage and output current.

2.4 Working of single phase full wave fully controlled converter with R-L loads.

- The circuit diagram and wave form of single phase full wave fully controlled converter or rectifier with R-L load are shown below.

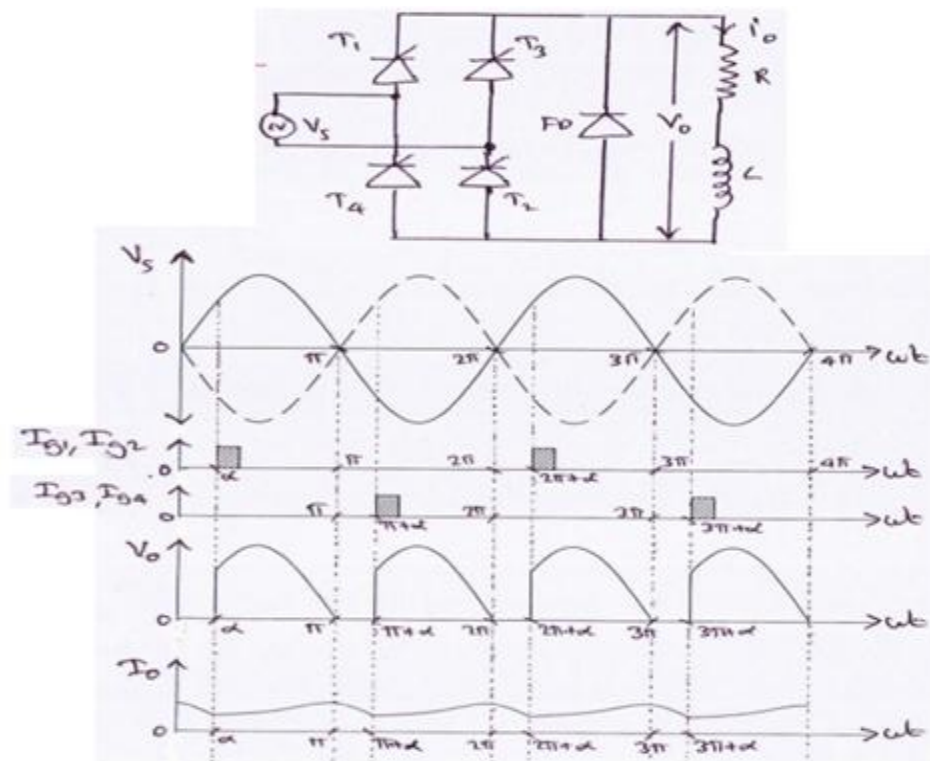


- The circuit consist of four thyristors T_1, T_2, T_3 and T_4 , a voltage source and a RL load.
- During the positive half cycle of the ac supply the thyristors T_1 and T_2 are forward biased but it does not conduct until a gate supply is applied to it.
- When a gate pulse is given to the thyristor T_1 and T_2 at $\omega t = \alpha$, it gets turned ON and begins to conduct.
- When the thyristors T_1 and T_2 are ON, the input voltage is applied to the load but due to the inductor present in the load the current through the load builds up slowly through the path V_s - T_1 -Load- T_2 - V_s .
- During the negative half cycle, T_3 & T_4 are forward biased, the thyristor T_1 and T_2 gets reverse biased but the current through them is not zero due to the inductor and does not turns OFF.
- The current through the inductor begins to decay to zero and T_1 & T_2 conducts for a small duration in negative half cycle.
- When a gate pulse is given to the thyristor T_3 & T_4 at $\omega t = \pi + \alpha$, it gets turned ON and begins to conduct.
- When the thyristor T_3 & T_4 are ON, the load current shifts its path to T_3 & T_4 and turns off T_1 & T_2 at $\omega t = \pi + \alpha$.

- When T3 & T4 are ON, the current through the load builds up slowly through the path V_s -T3-Load-T4- V_s .
- The load receives voltage during both the half cycles.
- The average value of output voltage can be varied by varying the firing angle α .
- The waveform shows the plot of input voltage, output voltage and output current.

2.4 Working of single phase full wave fully controlled converter with R-L load & Freewheeling Diode.

- The circuit diagram and wave form of single phase full wave fully controlled converter or rectifier with R-L load and freewheeling diode are shown below.

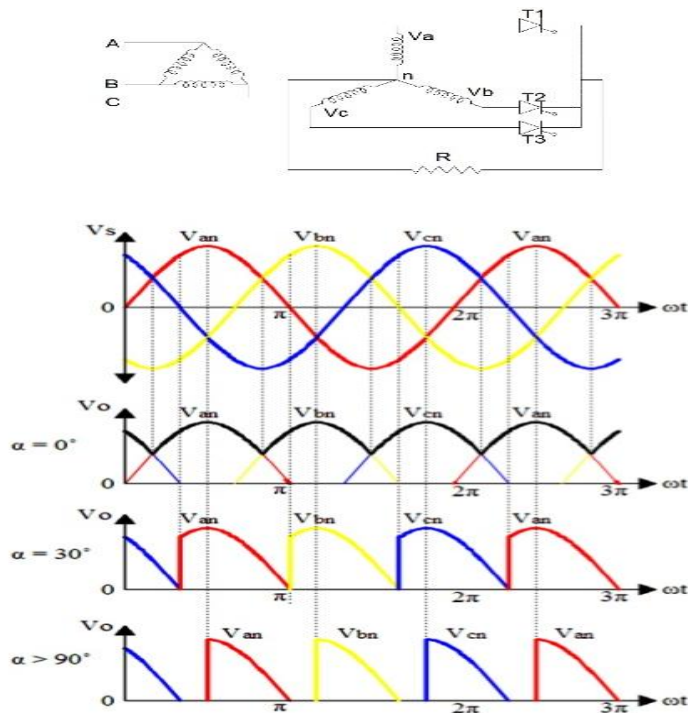


- The circuit consists of four thyristors T1,T2,T3,T4, a voltage source V_s , a RL load and a freewheeling diode across the load.
- During the positive half cycle of the input voltage the thyristors T1 & T2 are forward biased but it does not conduct until a gate signal is applied to it.
- When a gate pulse is given to the thyristor T1 & T2 at $\omega t = \alpha$, it gets turned ON and begins to conduct.
- When T1 & T2 are ON, the input voltage is applied to the load but due to the inductor present in the load, the current through the load build up slowly through the path V_s -T1-Load-T2- V_s .
- During the negative half cycle at $\omega t = \pi$, T3&T4 are forward biased, the thyristor T1 & T2 gets reverse biased and the current shifts its path to the freewheeling diode and circulates through the loop FD-R-L-FD thus T1 & T2 turns off at $\omega t = \pi$.

- When a gate pulse is given to thyristor T3 & T4 at $\omega t = \pi + \alpha$, it gets turned ON and begins to conduct, the current through the load builds up slowly through the path Vs-T3-Load-T4-Vs.
- During the next positive half cycle (at $\omega t = 2\pi$), T1 & T2 are forward biased, the thyristor T3 & T4 gets reverse biased and the current shifts its path to freewheeling diode and circulates through the loop FD-R-L-FD thus T3 & T4 turns off at $\omega t = 2\pi$.
- The average value of output voltage can be varied by varying the firing angle α .

2.5 Working of three-phase half wave controlled converter with Resistive load.

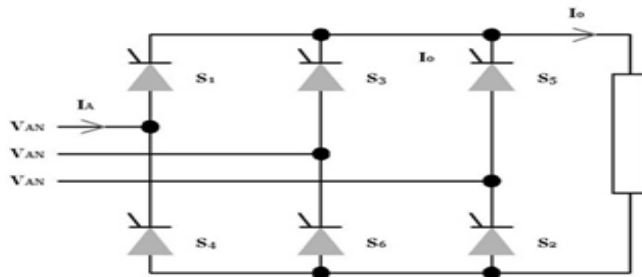
- The circuit diagram and wave form of three-phase half wave controlled converter with Resistive load are shown below.



- The circuit consists of a delta star transformer and three thyristors T1, T2, T3 which are connected on the secondary star connected winding and a resistive load.
- When V_a is positive, T1 becomes forward biased and conducts. During the negative cycle of V_a , T1 turns off.
- Similarly T2 and T3 conduct only during the positive cycles of V_b and V_c respectively.
- The average output voltage can be varied by varying the firing angles of the thyristors.
- The waveform shows the output voltage for various firing angles.
- In the waveform, V_a is denoted as V_{an} , V_b as V_{bn} , V_c as V_{cn} .

2.6 Working of three-phase fully controlled converter:

- The circuit diagram and wave form of three-phase fully controlled converter is shown below.



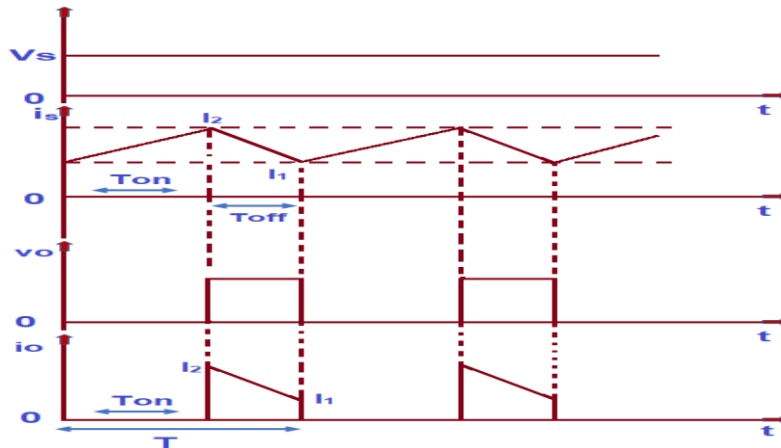
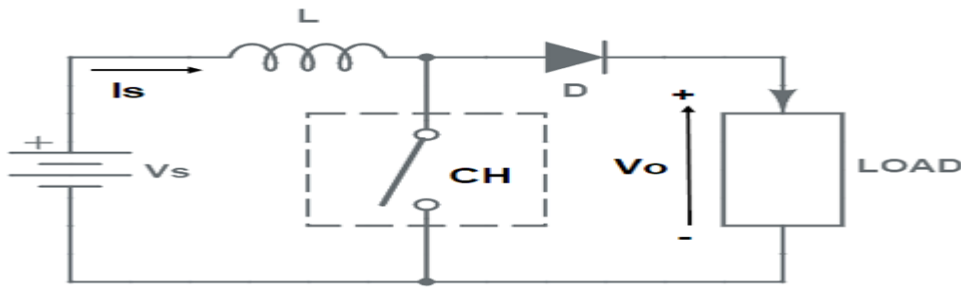
- When thyristor S2 is triggered at $\omega t = (5\pi/6 + \alpha)$, S1 becomes reverse biased and turns-off. The load current flows through the thyristor and through the supply phase winding 'b-n'. When S2 conducts the phase voltage V_{bn} appears across the load until the thyristor S3 is triggered.
- The 3-phase input supply is applied through the star connected supply transformer as shown in the figure. The common neutral point of the supply is connected to one end of the load while the other end of the load connected to the common cathode point.
- When the thyristor S1 is triggered at $\omega t = (\pi/6 + \alpha) = (30^\circ + \alpha)$, the phase voltage V_{an} appears across the load when S1 conducts. The load current flows through the supply phase winding 'a-n' and through thyristor S1 as long as S1 conducts.
- When the thyristor S3 is triggered at $\omega t = (3\pi/2 + \alpha) = (270^\circ + \alpha)$, S2 is reversed biased and hence S2 turns-off. The phase voltage V_{cn} appears across the load when S3 conducts.
- When S1 is triggered again at the beginning of the next input cycle the thyristor S3 turns off as it is reverse biased naturally as soon as S1 is triggered.
- For a purely resistive load where the load inductance ' $L = 0$ ' and the trigger angle $\alpha > (\pi/6)$, the load current appears as discontinuous load current and each thyristor is naturally commutated when the polarity of the corresponding phase supply voltage reverses. The frequency of output ripple frequency for a 3-phase half wave converter is f_s , where f_s is the input supply frequency.

2.8 CHOPPER:

- A chopper is a static device that converts fixed DC input voltage to variable output voltage directly. Chopper are mostly used in electric vehicle, mini haulers.
- Chopper are used for speed control and braking. The systems employing chopper offer smooth control, high efficiency and have fast response.
- Generally chopper is two types 1> step up chopper. 2> step down chopper

2.8 Working principle of step up chopper :

- Step-up chopper is a static device whose average output DC voltage is greater than its input DC voltage.
- The circuit diagram and wave form of step up chopper is drawn below

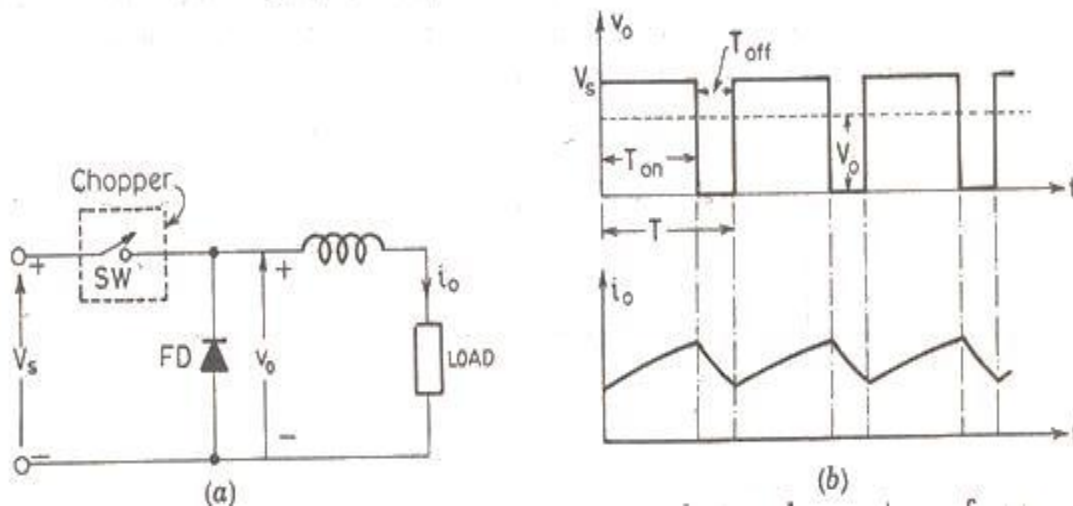


- When chopper (CH) is switched ON, the current will flow through the closed path formed by supply source V_s , inductor L and chopper CH . During this period, no current will flow through the load. Only source current i_s will flow and the value of load current i_o will be ZERO during the ON period.
- During the T_{ON} period, energy is stored in the inductor L . This energy storage in L is essential to boost the load output voltage above the source voltage. Therefore, a large value of L is essential in a step-up chopper.
- When the chopper CH is switched OFF, the current through the L can not die instantaneously rather it decays exponentially. Due to this behavior of L , it will force the current through the diode D and load for the entire time period T_{OFF} .
- Since, the current through the inductor L tends to decrease, the polarity of the emf induced in inductor L is reversed. As a result, the voltage across the load becomes equal to the sum of source voltage and emf induced in inductor. Thus, the output voltage exceeds the source voltage V_s .
- The load / output voltage $V_o = V_s + L(di/dt)$
- Thus, the circuit works as a step-up chopper. The voltage across the load increases because the inductor releases its stored energy to the load during the OFF period.

2.8 Working principle of step-down chopper :

- Step-down chopper is a static device whose average output DC voltage is lesser than its input DC voltage.

- The circuit diagram and wave form of step up chopper is drawn below



- When CH is switched ON, the source is directly connected to load and hence the output voltage V_o becomes equal to V_s . The time period for which chopper is kept ON is called ON Time of chopper and represented by T_{ON} . Thus, V_o will be equal to V_s for time T_{ON} .
- During the ON period of chopper, the current will build in the load exponentially and will reach its maximum value at the end of T_{ON} .
- Free-wheeling diode (D) is reversed biased during T_{ON} , hence it doesn't come into circuit during this period.
- When chopper switched OFF, the load is disconnected from the source V_s and hence load voltage V_o will be ZERO during the entire period for which CH is OFF. The time for which chopper is kept OFF is known as OFF time and represented by T_{OFF} .
- As the CH is switched OFF, the current through the inductor L (i_o) cannot suddenly drop to zero. Rather, it starts decreasing and hence the polarity of induced emf across the inductor reverses. This induced emf of inductor makes free-wheeling diode forward biased and hence, free-wheeling diode (D) acts as a short during T_{OFF} .
- Thus, the load current continues to decay through inductor L , free-wheeling diode D and load even though the source V_s is disconnected.
- Hence the output voltage is lesser than the input voltage.

2.9 Control modes of chopper :

There are two kinds of control strategies used in DC choppers namely time ratio control and current limit control.

1>Time Ratio Control

- In the time ratio control the value of the duty ratio, $K = T_{on} / T$ is changed. Here 'K' is called the duty cycle. There are two ways to achieve the time ratio control, namely variable frequency and constant frequency operation.

2>Current Limit Control

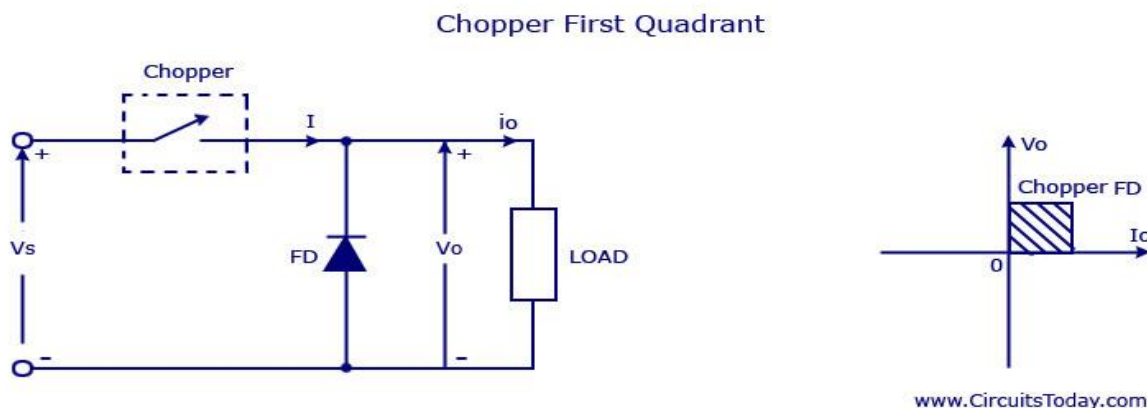
- In a DC to DC converter, the current value varies between the maximum as well as the minimum level of constant voltage. In this method, the DC to DC converter is turned ON & then OFF to confirm that current is preserved constantly between the upper limits and also lower limits. When the current energies beyond the extreme point, the DC-DC converter goes OFF.
- While the switch is in its OFF state, current freewheels through the diode and falls in an exponential manner. The chopper is turned ON when the flow of current spreads the minimum level. This technique can be utilized either when the ON time 'T' is endless or when the frequency $f=1/T$.

2.10 Operation of chopper in all four quadrants.

we can classify chopper circuits according to their working in any of these four quadrants as type A, type B, type C, type D and type E.

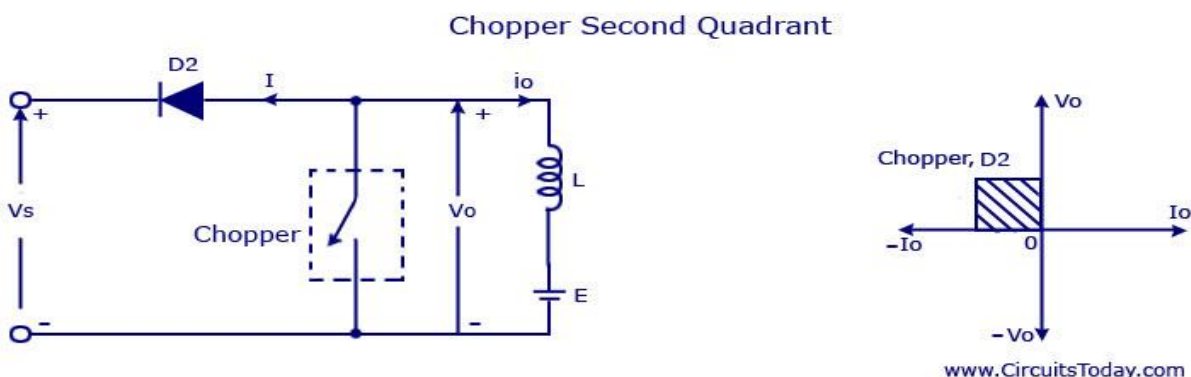
Type A Chopper or First-Quadrant Chopper

- This type of chopper is shown in the figure. It is known as first-quadrant chopper or type A chopper. When the chopper is on, $v_o = V_s$ as a result and the current flows in the direction of the load. But when the chopper is off v_o is zero but I_o continues to flow in the same direction through the freewheeling diode FD, thus average value of voltage and current say V_o and I_o will be always positive as shown in the graph.



- In type A chopper the power flow will be always from source to the load. As the average voltage V_o is less than the dc input voltage V_s -

Type B Chopper or Second-Quadrant Chopper

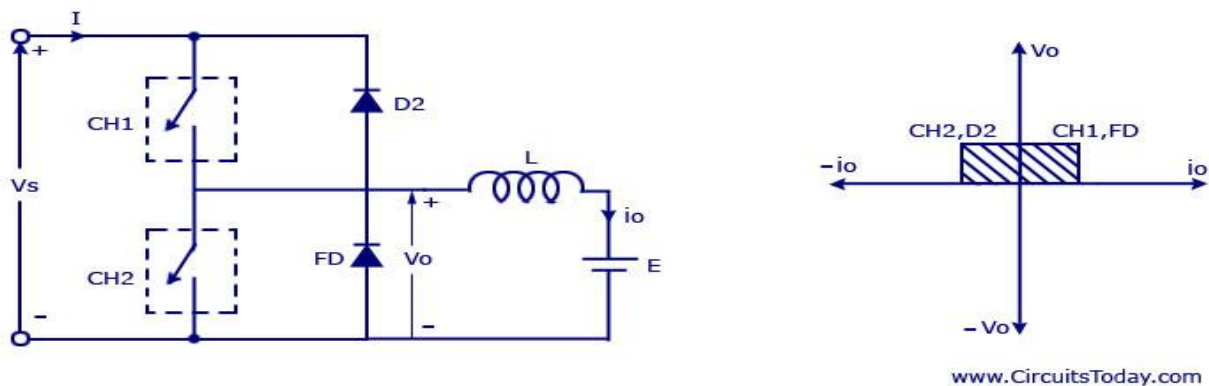


- In type B or second quadrant chopper the load must always contain a dc source E. When the chopper is on, v_0 is zero but the load voltage E drives the current through the inductor L and the chopper, L stores the energy during the time T_{on} of the chopper.
- When the chopper is off, $v_0 = (E + L \cdot di/dt)$ will be more than the source voltage V_s . Because of this the diode D2 will be forward biased and begins conducting and hence the power starts flowing to the source.
- The chopper may be on or off the current I_0 will be flowing out of the load and is treated negative. Since V_0 is positive and the current I_0 is negative, the direction of power flow will be from load to source. The load voltage $V_0 = (E + L \cdot di/dt)$ will be more than the voltage V_s so the type B chopper is also known as a step up chopper.

Type -C chopper or Two-quadrant type-A Chopper:

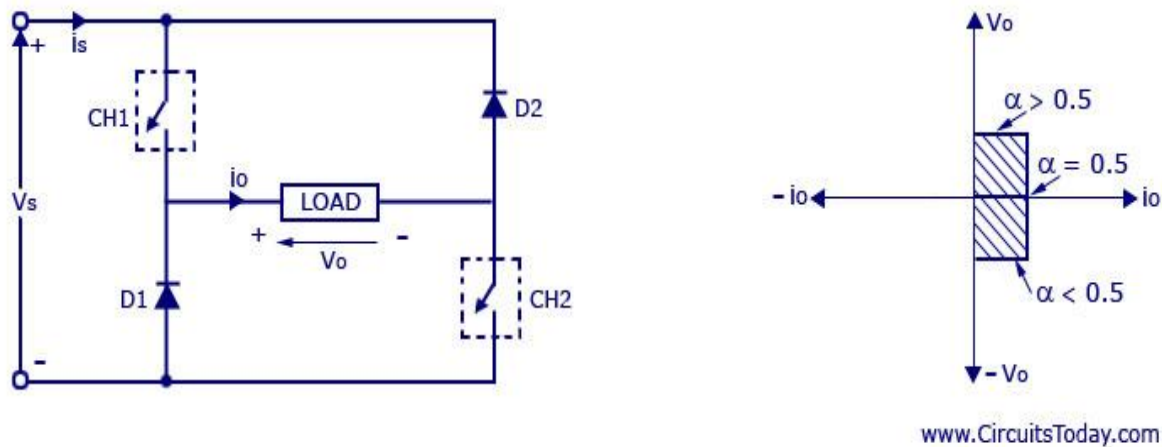
- Type C chopper is obtained by connecting type –A and type –B choppers in parallel.
- We will always get a positive output voltage V_0 as the freewheeling diode FD is present across the load.
- When the chopper is on the freewheeling diode starts conducting and the output voltage v_0 will be equal to V_s . The direction of the load current i_0 will be reversed. The current i_0 will be flowing towards the source and it will be positive regardless the chopper is on or the FD conducts.
- The load current will be negative if the chopper is or the diode D2 conducts. We can say the chopper and FD operate together as type-A chopper in first quadrant. In the second quadrant, the chopper and D2 will operate together as type –B chopper.
- The average voltage will be always positive but the average load current might be positive or negative. The power flow may be like the first quadrant operation i.e from source to load or from load to source like the second quadrant operation.
- The two choppers should not be turned on simultaneously as the combined action may cause a short circuit in supply lines.

Chopper Two Quadrant



Type D Chopper or Two-Quadrant Type –B Chopper

Two Quadrant Type B-chopper or D-chopper Circuit



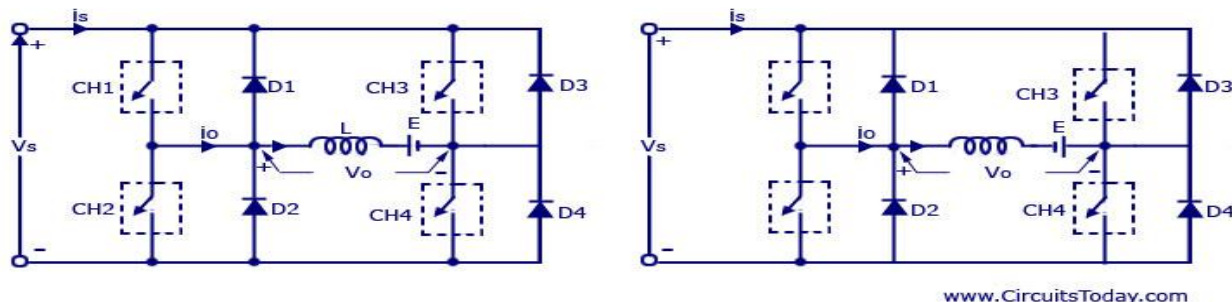
- When the two choppers are on the output voltage v_o will be equal to V_s . When $v_o = -V_s$ the two choppers will be off but both the diodes D1 and D2 will start conducting. V_o the average output voltage will be positive when the choppers turn-on the time T_{on} will be more than the turn off time T_{off} its shown in the wave form below. As the diodes and choppers conduct current only in one direction the direction of load current will be always positive.
- The power flows from source to load as the average values of both v_o and i_o is positive. From the wave form it is seen that the average value of V_o is positive thus the forth quadrant operation of type D chopper is obtained.
- From the wave forms the Average value of output voltage is given by

$$V_0 = (V_s T_{on} - V_s T_{off}) / T = V_s (T_{on} - T_{off}) / T$$

Type –E chopper or the Fourth-Quadrant Chopper

- Type E or the fourth quadrant chopper consists of four semiconductor switches and four diodes arranged in anti parallel. The 4 choppers are numbered according to which quadrant they belong. Their operation will be in each quadrant and the corresponding chopper only be active in its quadrant.

E-type Chopper Circuit Diagram With Load emf E and E Reversed



- **First Quadrant**

During the first quadrant operation the chopper CH4 will be on . Chopper CH3 will be off and CH1 will be operated. AS the CH1 and CH4 is on the load voltage v_0 will be equal to the source voltage V_s and the load current i_0 will begin to flow . v_0 and i_0 will be positive as the first quadrant operation is taking place. As soon as the chopper CH1 is turned off, the positive current freewheels through CH4 and the diode D2 . The type E chopper acts as a step- down chopper in the first quadrant.

- **Second Quadrant**

In this case the chopper CH2 will be operational and the other three are kept off. As CH2 is on negative current will starts flowing through the inductor L . CH2 ,E and D4. Energy is stored in the inductor L as the chopper CH2 is on. When CH2 is off the current will be fed back to the source through the diodes D1 and D4. Here $(E+L.di/dt)$ will be more than the source voltage V_s . In second quadrant the chopper will act as a step-up chopper as the power is fed back from load to source

- **Third Quadrant**

In third quadrant operation CH1 will be kept off , CH2 will be on and CH3 is operated. For this quadrant working the polarity of the load should be reversed. As the chopper CH3 is on, the load gets connected to the source V_s and v_0 and i_0 will be negative and the third quadrant operation will takes place. This chopper acts as a step-down chopper

- **Fourth Quadrant**

CH4 will be operated and CH1, CH2 and CH3 will be off. When the chopper CH4 is turned on positive current starts to flow through CH4, D2 ,E and the inductor L will store energy. As the CH4 is turned off the current is feedback to the source through the diodes D2 and D3 , the operation will be in fourth quadrant as the load voltage is negative but the load current is positive. The chopper acts as a step up chopper as the power is fed back from load to source.

SHORT QUESTIONS WITH ANSWER :

Q.1 Mention some of the applications of controlled rectifier.

1. Steel rolling mills, printing press, textile mills and paper mills employing dc motor drives.
2. DC traction
3. Electro chemical and electro-metallurgical process
4. Portable hand tool drives
5. Magnet power supplies
6. HVDC transmission system

Q.2 What is the function of freewheeling diodes in controlled rectifier? (S-09, W-11,17,19,20)

It serves two process.

1. It prevents the output voltage from becoming negative.
2. The load current is transferred from the main thyristors to the freewheeling diode, thereby allowing all of its thyristors to regain their blocking states.

Q.3 What are the advantages of freewheeling diodes in a controlled in a controlled rectifier?

1. Input power factor is improved.
2. Load current waveform is improved and thus the load performance is better.

Q.4 What is meant by delay angle?

The delay angle is defined as the angle between the zero crossing of the input voltage and the instant the thyristor is fired.

Q.5 What are the advantages of single phase bridge converter over single phase mid-point converter?

1. SCRs are subjected to a peak-inverse voltage of $2V_m$ in a fully controlled bridge rectifier. Hence for same voltage and current ratings of SCRs, power handled by mid-point configuration is about
2. In mid-point converter, each secondary winding should be able to supply the load power. As such, the transformer rating in mid-point converter is double the load rating.

Q.6 What is commutation angle or overlap angle?

The commutation period when outgoing and incoming thyristors are conducting is known as overlap period. The angular period, when both devices share conduction is known as the commutation angle or overlap angle.

Q.7 What are the different methods of firing circuits for line commutated converter?

1. UJT firing circuit.
2. The cosine wave crossing pulse timing control.
3. Digital firing schemes.

Q.8 What are the advantages of six pulse converter?

1. Commutation is made simple.
2. Distortion on the ac side is reduced due to the reduction in lower order harmonics.
3. Inductance reduced in series is considerably reduced.

Q.9 What is meant by dc chopper?

A dc chopper is a high speed static switch used to obtain variable dc voltage from a constant dc voltage.

Q.10 What are the applications of dc chopper? (W-06, S-09)

1. Battery operated vehicles
2. Traction motor control in electric traction
3. Trolley cars
4. Marine hoists
5. Mine haulers
6. Electric braking.

Q.11 What is meant by step-up and step-down chopper?

In a step- down chopper or Buck converter, the average output voltage is less than the input voltage. In a step- up chopper or Boost converter, the average output voltage is more than the input voltage.

Q.12 What is duty cycle of chopper? (W-16,17,19)

It is the ratio of Turn on time to the total chopping time of the chopper.
It is represented by α .

LONG QUESTIONS:

Q.1 Draw the circuit diagram of single phase half wave controlled rectifier with R-L load and freewheeling diode & explain the working when firing angle is changed. (W-07, 17,18)

Q.2 Explain with neat sketch the operation of a single phase fully controlled bridge rectifier.(S-09, W-17)

Q.3 Explain fully controlled bridge rectifier with R load.

Q.4 Explain single phase full wave fully controlled bridge rectifier with R-L load and freewheeling diode.(W-05,20)

Q.5 With necessary diagram explain the phase controlled technique.

Q.6 Explain about the A,B & C chopper.

Q.7 What is Chopper? Explain Step-down Chopper with a neat diagram? (W-10,11,14)

Q.8 Describe about the principle of Step-up Chopper.(W-10,16)

CHAPTER-3

UNDERSTAND THE INVERTERS AND CYCLO-CONVERTERS

Learning Objectives:

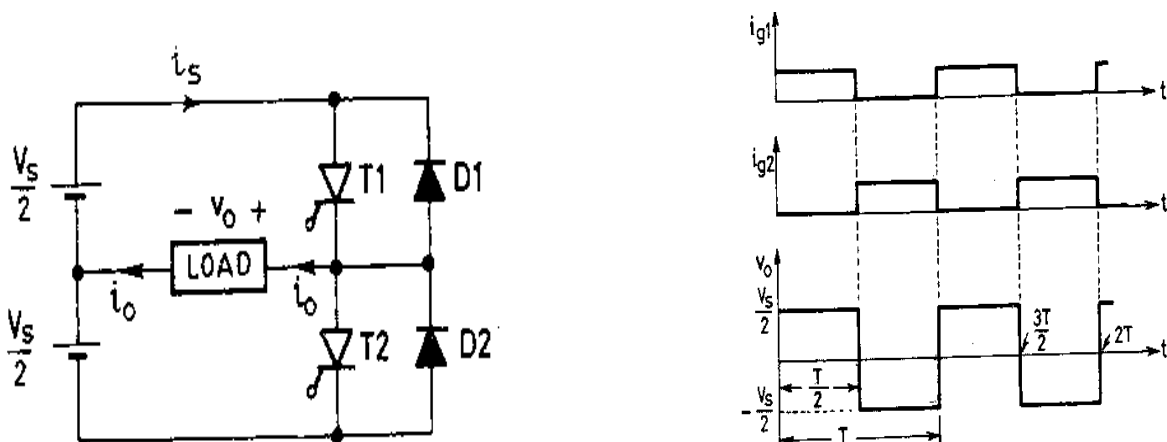
- 3.1 Classify inverters.
- 3.2 Explain the working of series inverter.
- 3.3 Explain the working of parallel inverter
- 3.5 Explain the basic principle of Cyclo-converter.
- 3.6 Explain the working of single-phase step up & step down Cyclo converter.
- 3.7 Applications of Cyclo-converter.

3.1 Classify inverters:

- Inverter is a static device which DC power to AC power at desired output voltage and frequency.
- Inverters are mainly classified into two types :
 1. Voltage source inverter (VSI)
 2. Current source inverter (CSI)
- According to the method of commutation inverters are classified as :
 1. Line commutated inverter.
 2. Force commutated inverter.
- According to the connection the inverters are classified as :
 1. Series inverter.
 2. Parallel inverter.
 3. Bridge inverter. (half bridge & full bridge)

Explain the working of single-phase half bridge voltage source inverter.

The circuit diagram and waveform of single phase half bridge voltage source inverter is shown below.

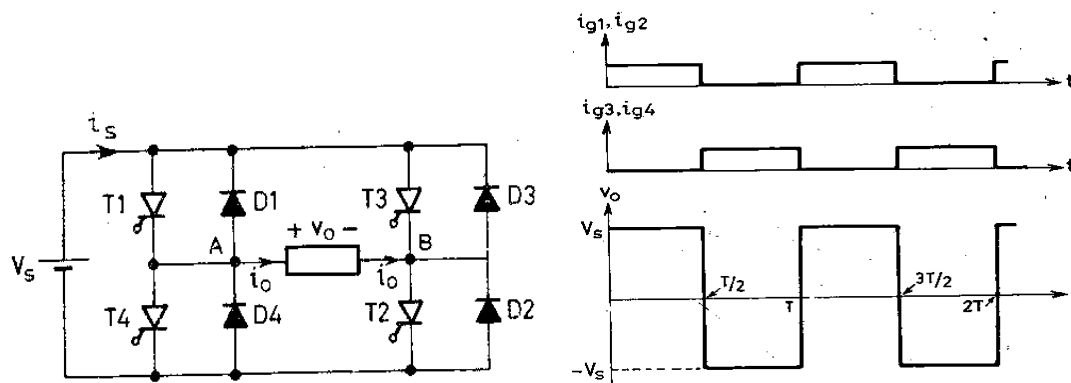


- It consists of two thyristors T1, T2, and two diodes D1, D2 and three wire supply, load and a DC source.
- Here i_{g1} and i_{g2} are the gate signals applied to the thyristor T1 & T2 respectively.
- For the time period 0 to $T/2$ the gate signal i_{g1} is applied to the SCR T1 so T1 conducts and the load is subjected to a voltage $V_o = V_s/2$ due to the upper voltage source $V_s/2$.

- At the time period $T/2$ thyristor T1 is commutated and the thyristor T2 is turned ON by applying gate signal I_{g2} .
- During the time period $T/2$ to T thyristor T2 conducts and the load is subjected to a voltage $V_o = -V_s/2$ due to the lower voltage source $V_s/2$.
- Thus the load voltage or output voltage V_o is an alternating voltage waveform of amplitude $V_s/2$ and of frequency $1/T$ Hz.
- Frequency of the inverter can be changed by controlling the time period T .
- In case of R-L load the energy is fed back to the DC source through the diodes D1 & D2 so the diodes are called as feedback diode.
- Feedback diodes are always connected antiparallelly with the main thyristors.

Explain the working of single-phase full bridge voltage source inverter.

- The circuit diagram and waveform of single phase full bridge voltage source inverter is shown below.



- It consists of four thyristors T1, T2, T3, T4, four diodes D1, D2, D3, D4, a DC voltage source and a load.
- Here I_{g1} , I_{g2} , I_{g3} , I_{g4} are the gate signals applied to the thyristors T1, T2, T3, T4 respectively for their conduction mode.
- For the time period 0 to $T/2$ the gate signals I_{g1} & I_{g2} are applied to the thyristors T1 & T2 respectively so T1 & T2 conduct thus load is subjected to a voltage $V_o = V_s$.
- At the time period $T/2$ the thyristors T1 & T2 are commutated and T3, T4 are turned ON by applying gate signal I_{g3} & I_{g4} .
- During the time period $T/2$ to T , thyristors T3, T4 conduct and load is subjected to a voltage $V_o = -V_s$.
- Thus the load voltage or output voltage V_o is an alternating voltage waveform of amplitude V_s and frequency $1/T$ Hz.
- Frequency of the inverter can be changed by controlling the time period.

3.2 Explain the working of series inverter :

- The commutating components L and C are connected in series with the load therefore this inverter is called as Series Inverter.
- The value of commutating components is selected such that the circuit becomes under damped.
- The anode current itself becomes zero in this inverter resulting the SCR turns off automatically therefore this inverter is also called as self commutated or load commutated inverter.

Power Circuit Diagram:

- The power circuit diagram of the series inverter is shown in the figure A.
- The SCR T1 and SCR T2 are turned on at regular interval in order to achieve desirable output voltage and output frequency.
- The SCR T2 is kept off at starting condition and polarity of voltage across capacitor is shown in the figure A.

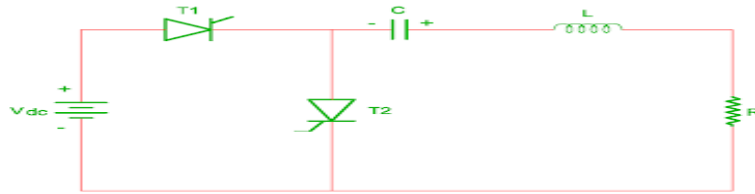


FIGURE A : BASIC SERIES INVERTER

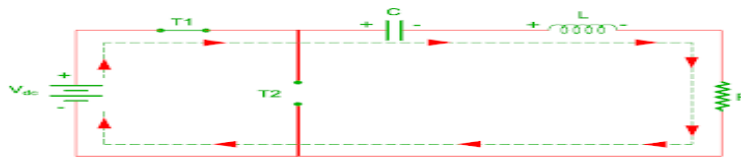


FIGURE B : EQUIVALENT CIRCUIT WHEN SCR T1 'ON'

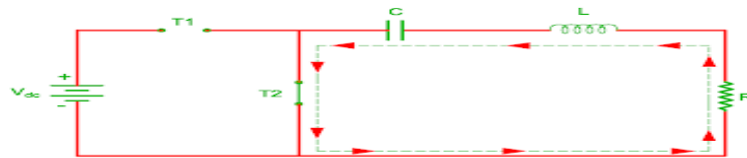


FIGURE C : EQUIVALENT CIRCUIT WHEN SCR T2 'ON'

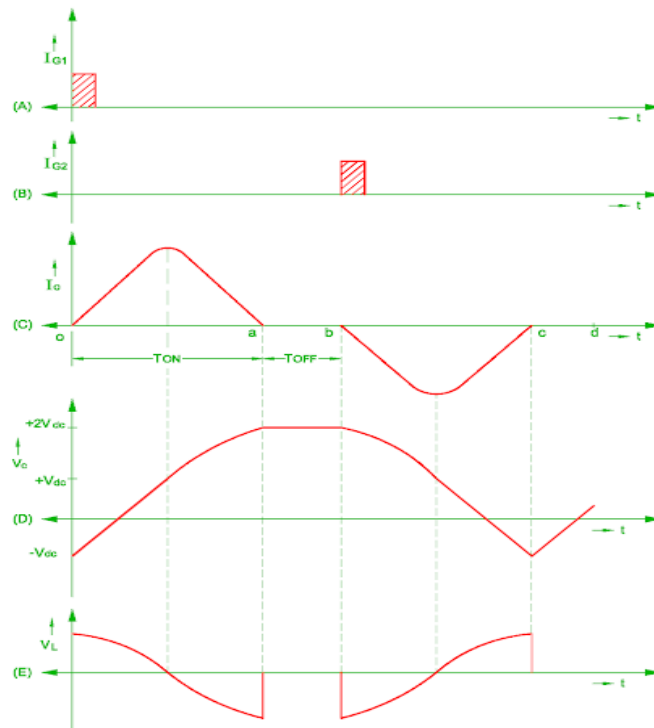


FIGURE D : VOLTAGE AND CURRENT WAVEFORMS OF SERIES INVERTER
(A) Gate pulse for SCR T1 (B) Gate pulse for SCR T2 (C) output current,
(D) Capacitor voltage (E) Load voltage

Operation:

Mode 1

- The voltage V_{dc} directly applies to RLC series circuit as soon as the SCR T1 is turned on.
- The polarity of capacitor charging is shown in the figure B.
- The nature of the load current is alternating as there is under damped circuit of the commutating components.
- The voltage across capacitor becomes $+V_{dc}$ when the load current becomes maximum.
- The voltage across capacitor becomes $+2V_{dc}$ when the load current becomes zero at point a (figure D).
- The SCR T1 automatically turns off at point a because the load current becomes zero.

Mode 2

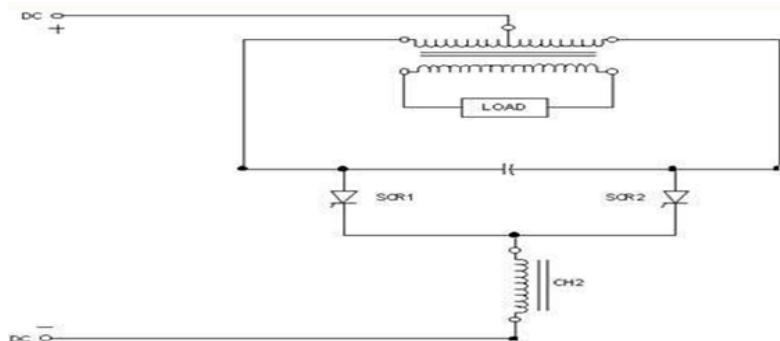
- The load current becomes zero from point a to b as the SCR T1 turns off in this time period.
- The SCR T1 and SCR T2 are turned off in this time duration and voltage across capacitor becomes equal to $+2V_{dc}$.

Mode 3

- The SCR T2 is turned on at point b due to it receives positive capacitor voltage.
- The discharging of capacitor is done through SCR T2 and R-L circuit as shown in the figure C.
- The load current becomes zero after it becomes maximum in the negative direction.
- The capacitor discharges from $+2V_{dc}$ to $-V_{dc}$ during this time and SCR T2 turns off automatically at point C due to load current becomes zero.
- The SCR T2 turns off during point C to D and SCR T1 again turns on. This way cycle repeats after it completes one turn.
- The time duration ab and cd must be greater than the SCR specific turn off time and it is called as dead zone.

3.3 Explain the working of parallel inverter:

- The single phase parallel inverter circuit consists of two SCRs T1 and T2, an inductor L, an output transformer and a commutating capacitor C.
- The output voltage and current are V_o and I_o respectively.
- The function of L is to make the source current constant. During the working of this inverter, capacitor C comes in parallel with the load via the transformer. So it is called a parallel inverter.



- The operation of this inverter can be explained in the following modes.

Mode I

- In this mode, SCR T1 is conducting and a current flow in the upper half of primary winding. SCR T2 is OFF. As a result an emf V_s is induced across upper as well as lower half of the primary winding.
- In other words total voltage across primary winding is $2V_s$. Now the capacitor C charges to a voltage of $2V_s$ with upper plate as positive.

Mode II

- At time t_0 , T2 is turned ON by applying a trigger pulse to its gate.
- At this time $t=0$, capacitor voltage $2V_s$ appears as a reverse bias across T1, it is therefore turned OFF. A current I_o begins to flow through T2 and lower half of primary winding.
- Now the capacitor has charged (upper plate as negative) from $+2V_s$ to $-2V_s$ at time $t=t_1$. Load voltage also changes from V_s at $t=0$ to $-V_s$ at $t=t_1$.

Mode III

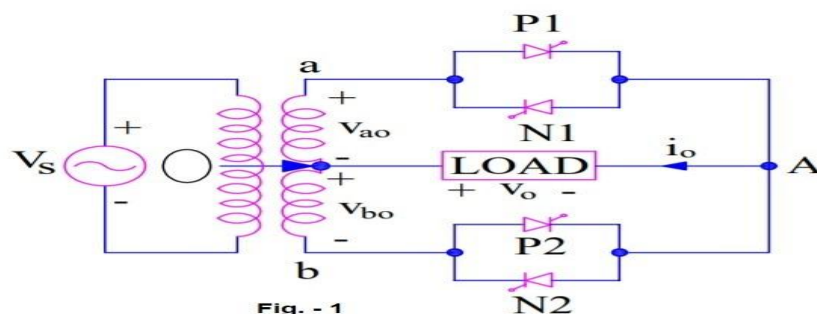
- When capacitor has charged to $-V_s$, T1 may be turned ON at any time. When T1 is triggered, capacitor voltage $2V_s$ applies a reverse bias across T2, it is therefore turned OFF.
- After T2 is OFF, capacitor starts discharging, and charged to the opposite direction, the upper plate as positive.

3.5 Explain the basic principle of Cyclo-converter:

- A cyclo-converter is a device that converts AC, power at one frequency into AC power of an adjustable but lower frequency without any direct current.



Circuit Diagram:



- The circuit consists of a single phase transformer with mid tap on the secondary winding and four thyristors.
- Two of these thyristors P1 & P2 are for positive group.
- Here positive group means when either P1 or P2 conducts, the load voltage is positive.
- Other two thyristors N1 & N2 are for negative group.
- Load is connected between secondary winding mid-point O and terminal A.
- The load is assumed resistive for simplicity. Assumed positive direction for voltage and current are marked in the circuit diagram.

Types of Cycloconverter:

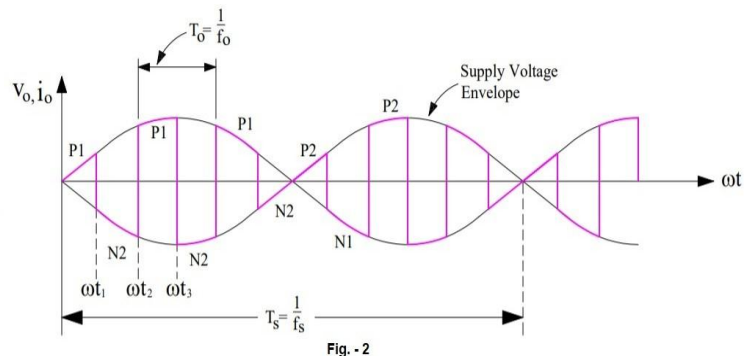
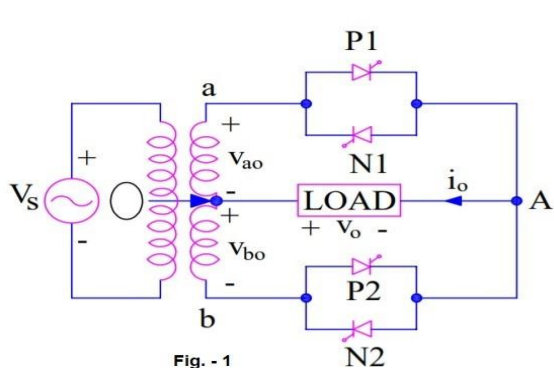
Mainly there are two types cycloconverter according to the output frequency

1. Step-up cycloconverters
2. Step-down cycloconverters.

3.6 Explain the working of single-phase step up Cyclo-converter :

It can provide an output having the frequency greater than the input frequency by using line commutation.

The circuit diagram and waveform are drawn below :



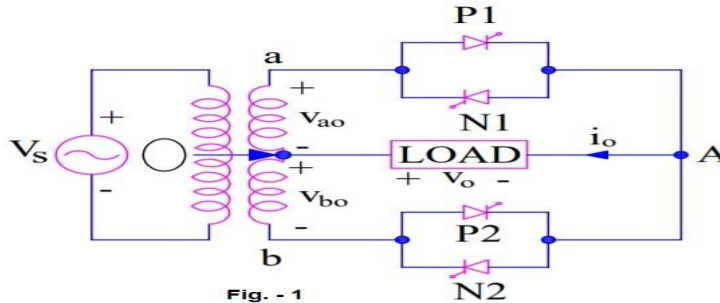
Operation:

- During the positive half cycle of input supply voltage, positive group thyristors P1 & N2 are forward biased for $\omega t = 0$ to $\omega t = \pi$. As such SCR P1 is fired to turn it ON at $\omega t = 0$ such that load voltage is positive with terminal A positive and O negative.
- The load voltage, thus, follows the positive envelop of the input supply voltage.
- At some time instant $\omega t = \omega t_1$, the conducting thyristor P1 is force commutated and the forward biased thyristor N2 is fired to turn it ON.
- During the period N2 conducts, the load voltage is negative because O is positive & A is negative this time. The load or output voltage traces the negative envelop of the supply voltage. This is shown in figure below.
- At $\omega t = \omega t_2$, N2 is force commutated and P1 is turned ON. The load voltage is now positive and follows the positive envelop of the supply voltage.
- At $\omega t = \pi$, terminal "b" is positive with respect to terminal "a"; both SCRs P2 & N1 are therefore forward biased from $\omega t = \pi$ to $\omega t = 2\pi$. At $\omega t = \pi$, N2 is force commutated and forward biased SCR P2 is turned ON.
- The load voltage is positive and follows the positive envelop of supply voltage.
- If the supply frequency is f_s and output frequency is f_o , P2 will be force commutated at $\omega t = (1/2f_s) + (1/2f_o)$.
- When P2 is force commutated, forward biased SCR N1 is turned ON. This time, the load voltage is negative and follows the negative envelop of the supply input.
- In this manner, SCRs P1, N2 for the first half cycle; P2, N1 in the second half cycle and so on are switched alternately between positive and negative envelops at a high frequency.
- This results in output frequency f_o more than the input supply frequency f_s .

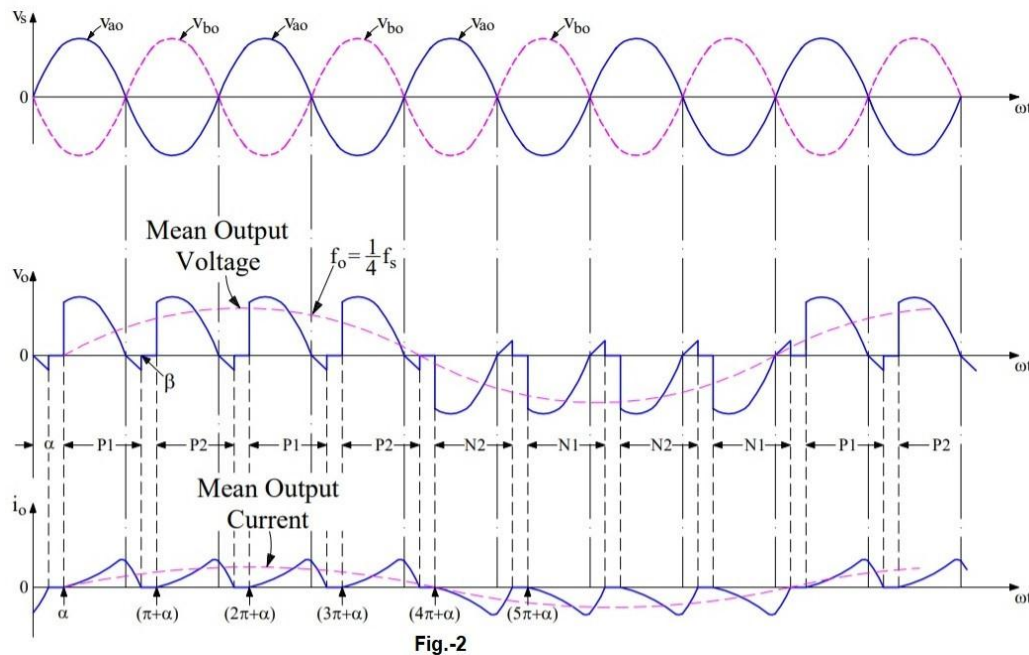
3.6 Explain the working of single-phase step down Cyclo-converter:

- It provides output having lower frequency than the input frequency by using forced commutation.
- The working principle of step-down cyclo-converter is explained for discontinuous and continuous load current.
- The load is assumed to be comprised of resistance (R) & inductance (L).

The circuit diagram and waveform are drawn below:



Discontinuous Load Current:



- For positive cycle of input AC supply, the terminal A is positive with respect to point O. This makes SCR P1 forward biased. The forward biased SCR P1 is triggered at $\omega t = 0$. With this, load current i_o starts building up in the positive direction from A to O.
- Load current i_o becomes zero at $\omega t = \beta > \pi$ but less than $(\pi + \alpha)$. The thyristor P1 is thus, naturally commutated at $\omega t = \beta$ which is already reversed biased after π .
- After half a cycle, b is positive with respect to O. Now forward biased thyristor P2 is fired at $\omega t = (\pi + \alpha)$. Load current is again positive from A to O and builds up from zero as shown in figure 2.
- At $\omega t = (\pi + \beta)$, i_o decays to zero and P2 is naturally commutated. At $\omega t = (2\pi + \alpha)$, P is again turned ON. Load current in figure-2 is seen to be discontinuous.

- After four positive half cycles of load voltage and load current, thyristor N2 is gated at $(4\pi+\alpha)$ when O is positive with respect to b.
- As N2 is forward biased, it starts conducting but the direction of load current is reverse this time i.e. it flows from O to A. After N2 is triggered, O is positive with respect to "a" but before N1 is fired, i_o decays to zero and N2 is naturally commutated.
- Now when N1 is gated at $(5\pi+\alpha)$, i_o again builds up but it decays to zero before thyristor N2 in sequence is again gated.
- In this manner, four negative half cycles of load voltage and load current, equal to number of positive half cycles of load voltage & current, are generated.
- It is clear that the output frequency of load voltage & current is $(\frac{1}{4})$ times of input supply frequency.

Continuous Load Current:

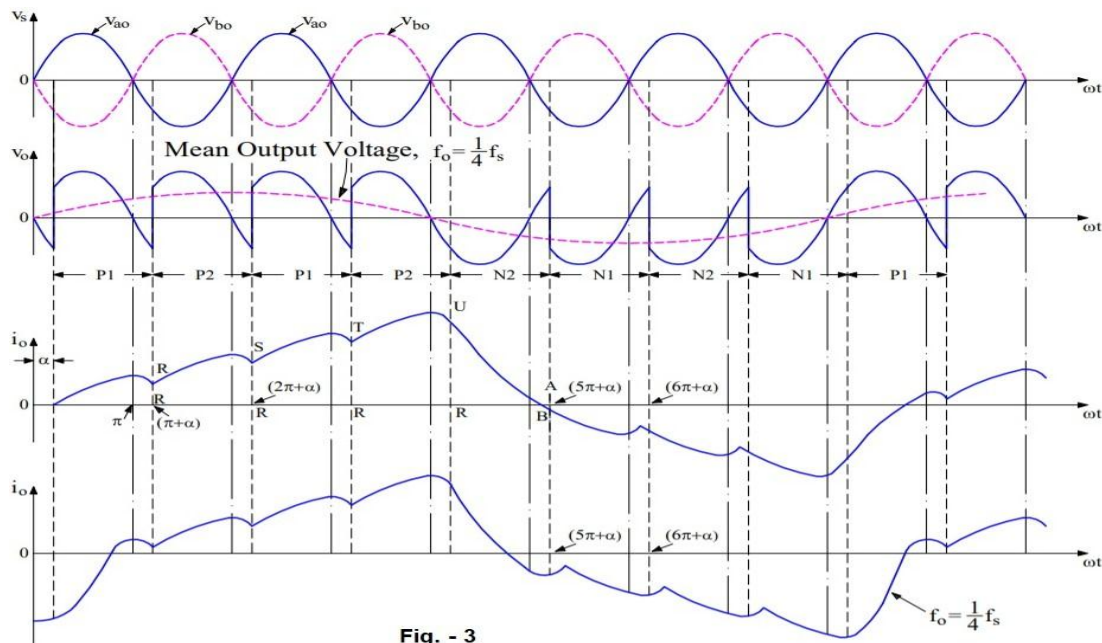


Fig. - 3

- When "a" is positive with respect to O in figure-1, P1 is triggered at $\omega t = \alpha$, positive output voltage appears across load and load current starts building up as shown in figure-3.
- At $\omega t = \pi$, supply and load voltages are zero. After $\omega t = \pi$, P1 is reversed biased. As load current is continuous, P1 is not turned OFF at $\omega t = \pi$.
- When P2 is triggered in sequence at $(\pi+\alpha)$, a reverse voltage appears across P1, it is therefore turned OFF by natural commutation.
- When P1 is commutated, load current has builds up to a value equal to RR. With the turn ON of P2 at $(\pi+\alpha)$, output voltage is again positive. As a consequence, load current builds up further than RR as shown in figure-3.
- At $(2\pi+\alpha)$, when P1 is again turned ON, P2 is naturally commutated and load current through P1 builds up beyond RS.
- At the end of four positive half cycles of output voltage, load current is RU.
- When N2 is triggered after P2, load is subjected to negative voltage cycle and load current i_o decreases from RU to negative AB.
- Now N2 is commutated and N1 is gated at $(5\pi+\alpha)$. Load current i_o becomes more negative than AB at $(6\pi+\alpha)$, this is because with N1 ON, load voltage is negative.

- For four negative half cycles of output voltage, current i_o is shown in figure-3. Load current waveform is redrawn in the last waveform of figure-3.
- The mean waveform of load voltage is also shown in load voltage waveform.
- It is clear from the load current and mean load voltage waveform that the output frequency is one fourth of the input supply frequency i.e. $f_o = (\frac{1}{4})f_s$.

3.7 Applications of Cyclo-converter :

1. Speed control of high power AC drive.
2. Induction Heating.
3. Static VAR compensation.
4. For converting variable speed alternator voltage to constant frequency output voltage for use as power supply in aircraft or shipboard.

SHORT QUESTIONS WITH ANSWER:

Q.1 State the function of the cycloconverter. (W-18,19)

Ans : The function of the cycloconverter is to convert constant voltage, constant frequency into variable voltage, and variable frequency without any intermediate stage.

Q.2 Describe the Principle of operation of the cycloconverter.

Ans: The cycloconverter consists of dual converter in which one converter works as positive converter whereas the other as the negative converter.

The firing angle of the both converter are adjusted such that

$$\alpha_p + \alpha_n = \pi$$

α_p = Firing angle of positive converter

α_n = Firing angle of negative converter.

Q.3 Describe the different types of cycloconverter.

Ans: Types of cycloconverter

According to frequency : (1) Step up cycloconverter and

(2) Step down cycloconverter

According to output voltage : (1) Single phase to single phase :

(a) Centre taped cycloconverter .

(b) Bridge configuration cycloconverter.

(2) Single phase to three phase

(3) Three phase to three phase.

Q.4 Describe the advantages and disadvantages of the cycloconverter.

Ans: Advantages :

- Higher efficiency due to single stage conversion.
- All the cycloconverter works on line commutation except step up cycloconverter therefore it is not necessary for extra commutating components.
- The power transfer from supply to load and vice versa at any power factor.
- It can operate at distorted output waveform in the case of one SCR gets damaged.

Disadvantages:

- Control circuit becomes complex due to higher number of SCRs.
- Low power factor for low output voltage
- The supply should be short circuited due to failure of commutation circuit.

Q.5 State the applications of the cycloconverter. (W-18,19)

Ans: The application of Cycloconverter are:

- Speed control of AC drives.
- Grinding mill drives.
- Induction heating.
- Variable frequency supply for shipyard or aircraft.
- Static VAr generation.
- HVDC transmission line.

Q.6 Describe the function of the Inverter. (W-11,16)

Ans: The function of the inverter is to convert fixed DC into variable voltage, variable frequency alternating supply.

Q.7 Define Series Inverter .

Ans: The commutating components L and C are connected in series with the load therefore this inverter is called as Series Inverter.

Q.8 Differentiate between Voltage Source Inverter (VSI) –Current Source Inverter (CSI).

Ans:

- The output voltage remains constant for a given type of load in the VSI whereas the input current remains constant in the CSI.
- A large capacitor is connected at the input side of the VSI whereas a large inductor is connected at the input side of the CSI.

LONG QUESTIONS:

Q.1 what are the different types of inverter and explain the working of series inverter with neat diagram and draw its waveform.(W-17,18)

Q.2 Explain the working of 1-ph parallel inverter with neat diagram.(W-09)

Q.3 Explain the principle of Cyclo-converter & its operation. (S-09,W-14)

Q.4 Explain about the 1-ph to 1-ph Cyclo-converter with resistive load. (W-16,17,18.S-19)

Q.5 Explain with neat circuit diagram , Step-up and step-down midpoint Cyclo-converter.(W-19,20)

Q.6 Explain the operation of 1-ph half bridge voltage source inverter with resistive load.(W-19)

Q.7 Explain the working of 1-ph parallel inverter with a neat diagram.(W-19)

CHAPTER-4

UNDERSTAND APPLICATIONS OF POWER ELECTRONIC CIRCUITS

Learning Objectives:

- 4.1 List applications of power electronic circuits.
- 4.2 List the factors affecting the speed of DC Motors.
- 4.3 Speed control for DC Shunt motor using converter.
- 4.4 Speed control for DC Shunt motor using chopper.
- 4.5 List the factors affecting speed of the AC Motors.
- 4.6 Speed control of Induction Motor by using AC voltage regulator.
- 4.7 Speed control of induction motor by using converters and inverters (V/F control).
- 4.8 Working of UPS with block diagram.
- 4.9 Battery charger circuit using SCR with the help of a diagram.
- 4.10 Basic Switched mode power supply (SMPS) - explain its working & applications

4.1 List applications of power electronic circuits :

The application of power electronics circuits are:

- Aerospace
- Commercial
- Industrial
- Residential
- Telecommunication
- Transportation
- Electric Drive

4.2 List the factors affecting the speed of DC Motors.

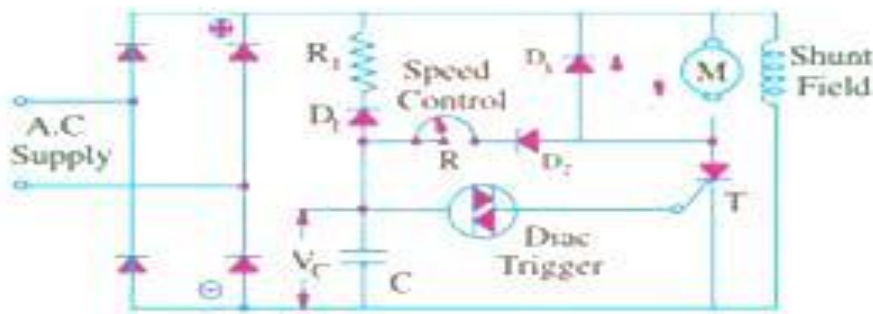
- The operation of a DC motor is typically designed such that when a current carrying conductor is placed within a magnetic field, there is bound to be themechanical force that goes through the conductors.
- The factors affecting DC control are :
 1. The applied voltage.
 2. The flux.
 3. The voltage across an armature.

Considering these factors, speed control can then be achieved through thefollowing techniques:

- i. Flux control method: This is done by varying the current via the fieldwinding, thus altering the flux.
- ii. Rheostatic control: changing the armature route resistance which alsochanges the applied voltage across the armature.
- iii. Voltage method: changing the applied voltage

4.3 Speed control for DC Shunt motor using converter:

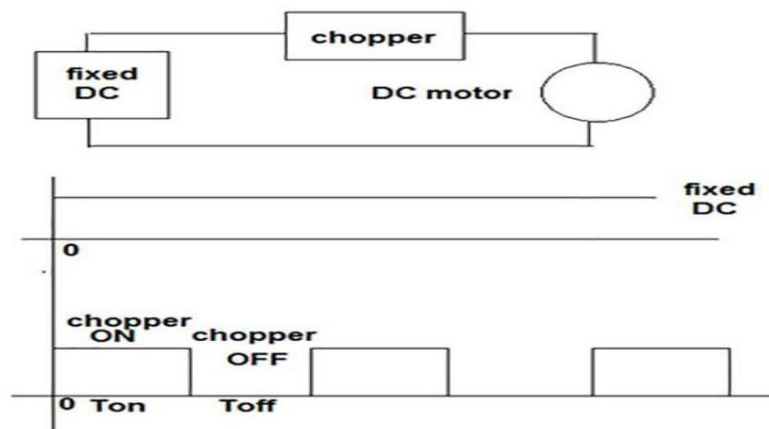
- The circuit uses a bridge circuit for full-wave rectification of the a.c. supply.
- The shunt field winding is permanently connected across the output of the bridge circuit. The armature voltage is supplied through thyristor T .



- The magnitude of this voltage can be changed by turning T_{ON} at different points in each half-cycle with the help of R .
- Free-wheeling diode D_3 provides a circulating current path for the energy stored in the armature winding at the time T turns OFF.
- At the beginning of each half-cycle, T is the OFF state and C starts charging up via motor armature, diode D_2 and speed-control variable resistor R . When voltage across C i.e., V_C builds up to the breakover voltage of diac, diac conducts and applies a sudden pulse to T there by turning it ON.
- Hence, power is supplied to the motor armature in next that half-cycle.
- At the end of each half-cycle, C is discharged through D_1 , R_1 and shunt field winding. The delay angle α depends on the time it takes V_C to become equal to the breakover voltage of the diac.
- By changing R , V_C can be made to build-up either slowly or quickly and thus change the angle. In this way, the average value of the d.c. voltage across the motor armature can be controlled.
- It further helps to control the motor speed because it is directly proportional to the armature voltage.
- Now, when load is increased, motor tends to slow down. Hence, E_b is reduced.
- The voltage of point A is increased because it is equal to the d.c. output voltage of the bridge rectifier.

4.4 Speed control for DC Shunt motor using chopper:

- chopper is a device that gives variable DC output from applied fixed DC input.
- It simply chops fixed DC and generates variable DC.



- As shown in figure the chopper supplies fixed DC voltage to motor.
- When chopper is ON motor gets supply but when chopper is off motor does not get the supply. So chopper is on for T_{on} time and it is off for T_{off} time, depending upon the T_{on} and T_{off} time the DC voltage applied to motor is

$$V_{dc} = [T_{on} / (T_{on} + T_{off})] \times V_{fixed}$$

But $T_{on} + T_{off} = T_{total}$

$$V_{dc} = [T_{on} / T_{total}] \times V_{fixed}$$

- Here T_{on} / T_{total} is called duty cycle. So as duty cycle is more the average DC voltage supplied to motor is more and so speed of motor is increased. So as duty cycle is varied by varying on and off time of chopper, the speed of motor can be varied.

4.5 List the factors affecting speed of the AC Motors :

The factors affecting speed of the AC Motors are affected by various factors like applied voltage, R_2' and frequency.

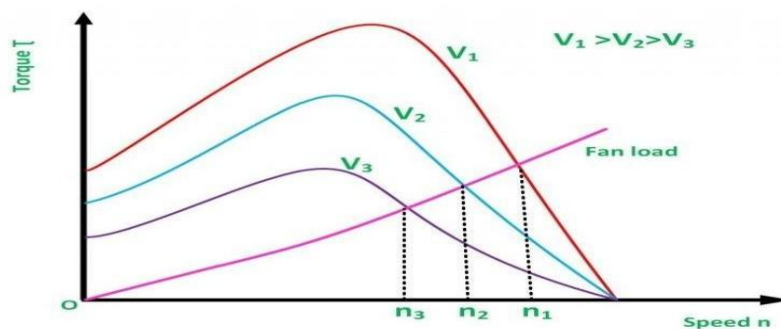
(a) Applied voltage : We know that $T \propto V$. Thus not only the stationary torque but also the torque under running conditions changes with change in supply voltage.

(b) Supply frequency : The major effect of change in supply frequency is on motor speed. The starting torque is reduced with increase in frequency.

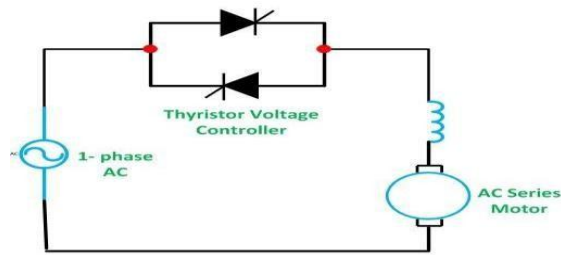
(c) Rotor resistance : The maximum torque produced does not depend on R_2' . However, with increase in R_2' , the starting torque increases. The slip at which T_{max} is reached increases too which means that T_{max} is obtained at lower motor speeds

4.6 Speed control of Induction Motor by using AC voltage regulator :

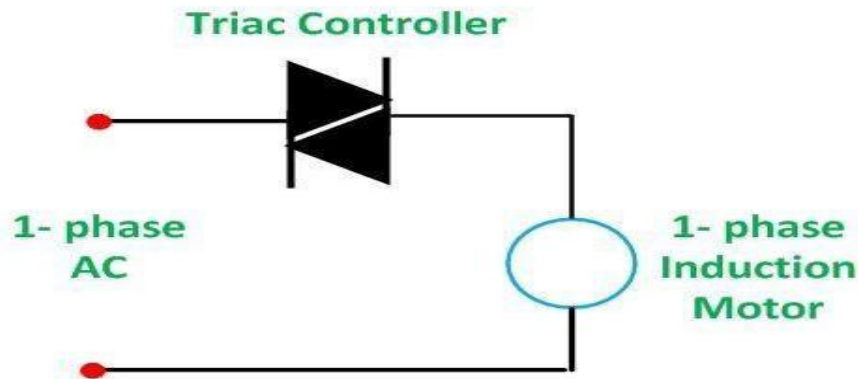
- Stator Voltage Control is a method used to control the speed of an Induction Motor.
- The speed of a three phase induction motor can be varied by varying the supply voltage.
- The Torque-Speed Characteristics of the three phase Induction motors for varying supply voltage and also for the fan load are shown below.



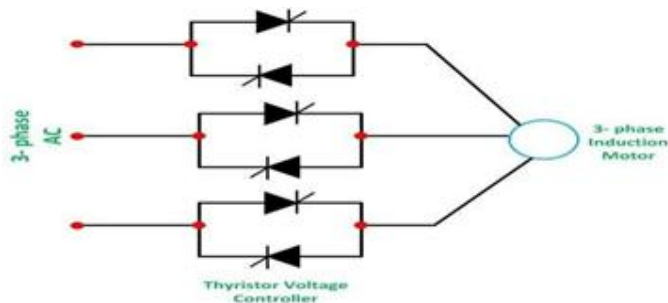
- The Thyristor voltage controller method is preferred for varying the voltage.
- For a single phase supply, two Thyristors are connected back to back as shown in the figure below.



- The domestic fan motors, which are single phase are controlled by a singlephase Triac Voltage Controller as shown in the figure below.



- Speed control is obtained by varying the firing angle of the Triac. These controllers are known as Solid State fan regulators.
- As the solid state regulators are more compact and efficient as compared to the conventional variable regulator. Thus, they are preferred over the normal regulator.
- In case of a three phase induction, motor three pairs of Thyristor are required which are connected back to back.
- Each pair consists of two Thyristor.
- The diagram below shows the Stator Voltage Control of the three phase inductionmotors by Thyristor Voltage Controller.



- Each pair of the Thyristor controls the voltage of the phase to which it is connected.
- Speed control is obtained by varying the conduction period of theThyristor.
- For lower power ratings, the back to back Thyristor pairs connectedin each phase is replaced by Traic.

4.7 Speed control of induction motor by using converters and inverters (V/F control).

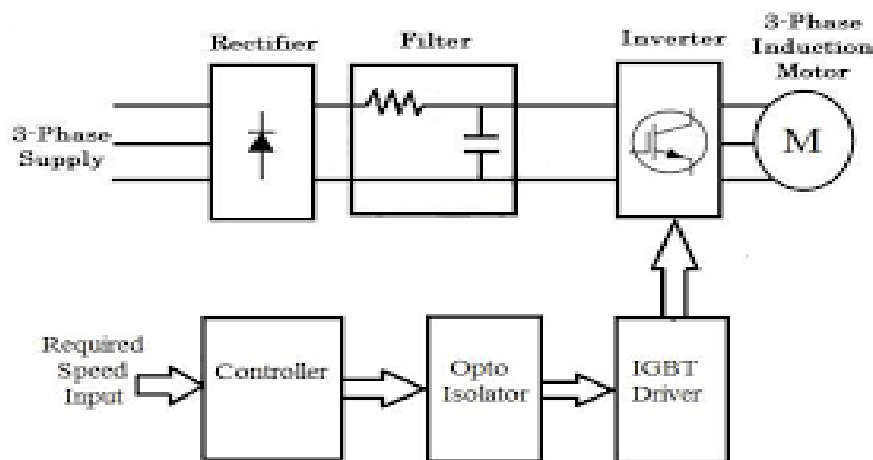
- Variable Frequency Control is a method which is used to control the speed of an induction motor.
- The synchronous speed and therefore, the speed of the motor can be controlled by varying the supply frequency.
- The synchronous speed of an induction motor is given by the relation shown below.

$$N_s = \frac{120f}{P}$$

- The EMF induced in the stator of the induction motor is given by the equationshown below.

$$E_1 = 4.44k_w1T_1$$

- Therefore, if the supply frequency is changed induced EMF will also change to maintain the same air gap flux.
- The terminal voltage V_1 is equal to the induced EMF E_1 if the stator voltage drop is neglected.
- In order to minimize the losses and to avoid the saturation, the motor is operated at rated air gap flux. This condition is obtained by varying the terminal voltage with frequency so as to maintain (V/f) ratio constant at therate value.
- This type of control is known as Constant Volts Per Hertz.
- Thus, the speed control of an induction motor using variable frequency supply requires a variable voltage power source.
- The variable frequency supply is obtained by the following converters.
 1. Voltage source inverter.
 2. Current source inverter.
 3. Cyclo converter



- An inverter converts a fixed voltage DC to a fixed or variable voltage AC with variable frequency.
- Cyclo converter converts a fixed voltage and fixed frequency AC to a variable voltage and variable AC frequency.
- The variable frequency control allows good running and transient performanceto be obtained from a cage induction motor.
- Cyclo converter controlled induction motor drive is suitable only for large power drives and to get lower speeds.

4.8 Working of UPS with block diagram :

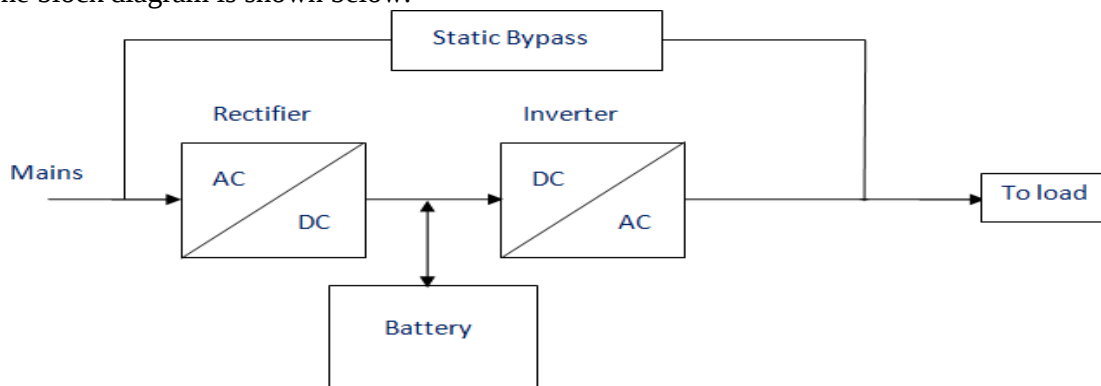
- The UPS stands for uninterruptible power source.
- It is an electrical device, gives emergency power to various loads when the input power typically fails.

UPS are mainly two types

1. Online UPS(uninterruptible power supply).
2. Offline UPS(uninterruptible power supply).

1.On-line UPS :

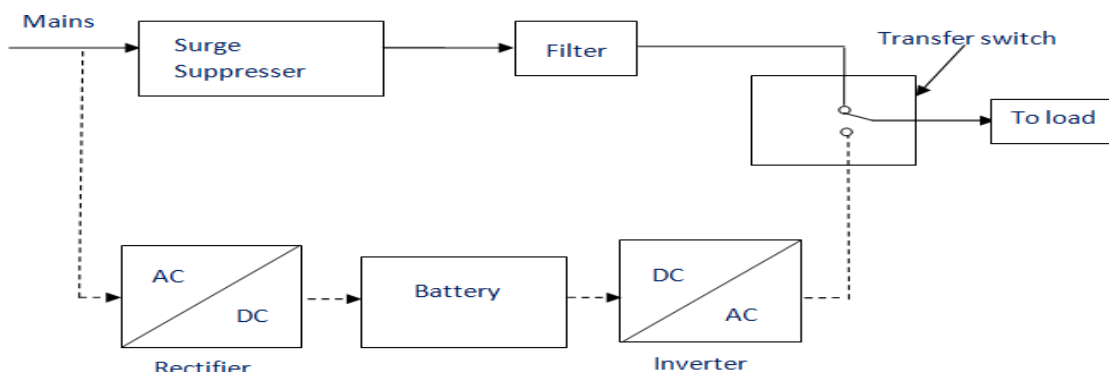
- In this type of UPS, double conversion method is used.
- Here, first the AC input is converted into DC by rectifying process for storing it in the rechargeable battery. This DC is converted into AC by the process of inversion and given to the load or equipment which it is connected.
- This type of UPS is used where electrical isolation is mandatory.
- Here, the rectifier which is powered with the normal AC current is directly driving the inverter. Hence it is also known as Double conversion UPS.
- The block diagram is shown below.



- When there is any power failure, the rectifier has no role in the circuit and the steady power stored in the batteries which is connected to the inverter is given to the load by means of transfer switch.
- Once the power is restored, the rectifier begins to charge the batteries. To prevent the batteries from overheating due to the high power rectifier, the charging current is limited.

Off-line UPS :

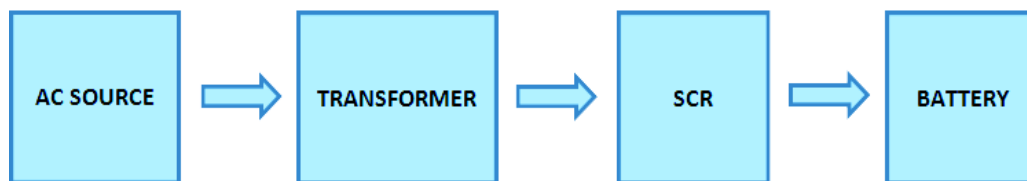
- The Off-line UPS is also called as Standby UPS system .
- The block diagram is shown below.



- Here, the primary source is the filtered AC mains .When the power breakage occurs, the transfer switch will select the backup source .Thus the stand by system will start working only when there is any failure in mains.
- In this system, the AC voltage is first rectified and stored in the storage battery connected to the rectifier.
- When power breakage occurs, this DC voltage is converted to AC voltage by means of a power inverter, and is transferred to the load connected to it.
- This is the least expensive UPS system and it provides surge protection in addition to back up.

4.9 Battery charger circuit using SCR with the help of a diagram:

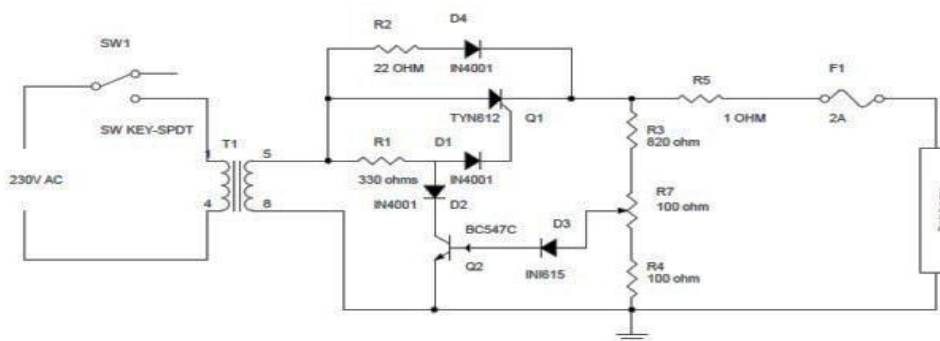
- The battery is charged with small amount of DC voltage. So to charge the battery with AC source some steps should follow , first limit the large AC voltage, need to filter the AC voltage to remove the noise, regulate and get the constant voltage and then give the resulting voltage to the battery for charging.
- Once charging is completed the circuit should automatically turned off.
- Block Diagram of Battery Charger Using SCR is drawn below:



- The AC source is given to the step down transformer which converts the large AC source into limited AC source, filter the AC voltage and remove the noise and then give that voltage to the SCR where it will rectify the AC and give the resulting voltage to the battery for charging.

Circuit Diagram :

The circuit diagram of the Battery Charger Circuit using SCR can be seen below :

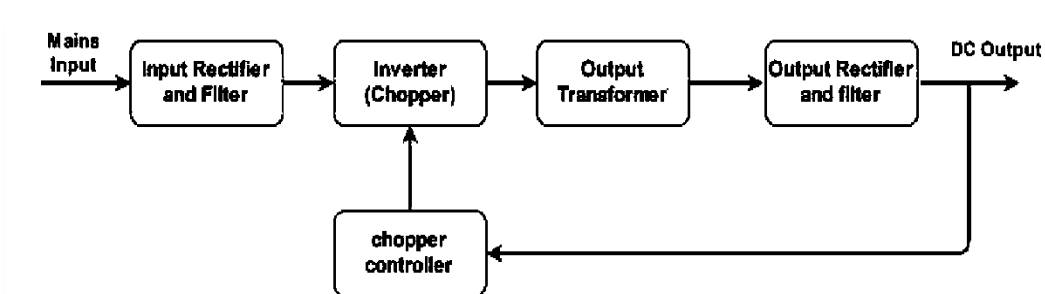


- The AC main voltage is given to the step down transformer the voltage should be down to 20V approx. the step down voltage is given to the SCR for rectification and SCR rectifies AC main voltage. This rectified voltage is used to charge battery.
- When the battery connector to the charging circuit, the battery will not be dead completely and it will get discharged this will give the forward bias voltage to the transistor through the diode D2 and resistor R7 which will get turned on. When the transistor is turned on the SCR will get off.

- When the battery voltage is dropped the forward bias will be decreased and transistor gets turned off. When the transistor is turned off automatically the diode D1 and resistor R3 will get the current to the gate of the SCR, this will trigger the SCR and get conduct. SCR will rectifies the AC input voltage and give to the battery through Resistor R6.
- This will charge the battery when the voltage drop in the battery decreases the forward bias current also gets increased to the transistor when the battery is completely charged the Transistor Q1 will be again turned on and turned off the SCR.

4.10 Basic Switched mode power supply (SMPS) - explain its working & applications:

- A switched-mode power supply (SMPS) is an electronic circuit that converts power using switching devices that are turned on and off at high frequencies, and storage components such as inductors or capacitors to supply power when the switching device is in its non-conduction state.
- A basic isolated AC to DC switched-mode power supply consists of:
 1. Input rectifier and filter.
 2. Inverter consisting of switching devices such as MOSFETs.
 3. Transformer.
 4. Output rectifier and filter.
 5. Feedback and control circuit



- The input DC supply from a rectifier or battery is fed to the inverter where it is turned on and off at high frequencies of between 20 KHz and 200 KHz by the switching MOSFET or power transistors.
- The high-frequency voltage pulses from the inverter are fed to the transformer primary winding, and the secondary AC output is rectified and smoothed to produce the required DC voltages.
- A feedback circuit monitors the output voltage and instructs the control circuit to adjust the duty cycle to maintain the output at the desired level.

Application of SMPS:

1. Machine tool industries
2. Security Systems (Closed circuit cameras)
3. Support supplies with PLC's
4. Personal Computers.
5. Mobile Phone chargers.

Short Questions with Answer:

Q.1 What are the applications of power electronics circuits?

Ans-The application of power electronics circuits are:

- Aerospace
- Commercial
- Industrial
- Residential
- Telecommunication
- Transportation
- Electric Drive

Q.2 What are the factors affecting speed of DC motor?

Ans- The factors affecting DC control are :

1. The applied voltage.
2. The flux.
3. The voltage across an armature

Q.3 What is SMPS & Why it is preferred in comparison to linear regulator?(W-10,14.20)

Ans- **SMPS** means Switch mode power supply. For medium to high power application and also for the power supply of computers, it is essential. It has low power dissipation, high efficiency, small size and low weight in comparison to linear regulator

Q.4 What is the utility of UPS?(S-09)

Ans-The utility of UPS are

- i. In medical intensive care systems
- ii. Chemical plant process control
- iii. Safety monitors or major computer installation

Q.5 What are the uses of no-break UPS?(W-19)

Ans-Uses of no break UPS-

1. Induction motor drive
2. ICU medical equipment
3. Chemical plant process
4. Control, safety monitor
5. Major computer installations communication links
6. Microwave relay station

Long questions:

1. Explain with neat sketch the operation of UPS.(S-07,09,W-16,17)
2. What are the difference between online UPS and off line UPS?(W-16)
3. Explain Speed control of induction motor by using converters and inverters.
4. Explain Speed control of Induction Motor by using AC voltage regulator.
5. Explain the working and application of SMPS.

CHAPTER-5

PLC AND ITS APPLICATIONS

Learning Objectives:

- 5.1 Introduction of Programmable Logic Controller(PLC)
- 5.2 Advantages of PLC
- 5.3 Different parts of PLC by drawing the Block diagram and purpose of each part of PLC.
- 5.4 Applications of PLC
- 5.5 Ladder diagram
- 5.6 Description of contacts and coils in the following states
i) Normally open ii) Normally closed iii) Energized output iv) latched Output v) branching
- 5.7 Ladder diagrams for i) AND gate ii) OR gate and iii) NOT gate.
- 5.8 Ladder diagrams for combination circuits using NAND, NOR, AND, OR and NOT
- 5.9 Timers-i) T ON ii) T OFF and iii) Retentive timer
- 5.10 Counters-CTU, CTD
- 5.11 Ladder diagrams using Timers and counters
- 5.12 PLC Instruction set
- 5.13 Ladder diagrams for following
(i) DOL starter and STAR-DELTA starter (ii) Stair case lighting (iii) Traffic light Control
(iv) Temperature Controller
- 5.14 Special control systems- Basics DCS & SCADA systems
- 5.15 Computer Control–Data Acquisition, Direct Digital Control System (Basics only)

5.1 Introduction of Programmable Logic Controller(PLC) :

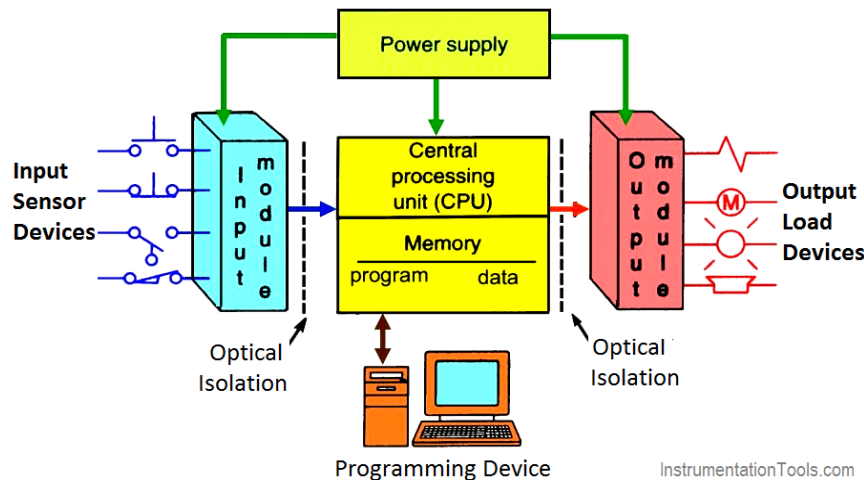
- PLC stands for Programmable Logic Controllers.
- It is basically used to control automated systems in industries.
- It is one of the most advanced and simplest forms of control systems which are now replacing hard-wired logic relays at a large scale.

5.2 Advantages of PLC :

- They are user friendly and easy to operate.
- They eliminate the need for hard-wired relay logic.
- They are fast.
- It is suitable for automation in industries.
- Its input and output modules can be extended depending upon the requirements.

5.3 Different parts of PLC by drawing the Block diagram and purpose of each part of PLC :

A basic PLC system consists of the following sections:



Input/ Output Section:

- The input section or input module consists of devices like sensors, switches, and many other real-world input sources.
- The input from the sources is connected to the PLC through the input connector rails.
- The output section or output module can be a motor or a solenoid or a lamp or a heater, whose functioning is controlled by varying the input signals.

CPU or Central Processing Unit:

- It is the brain of the PLC.
- It can be a hexagonal or an octal microprocessor.
- It carries out all the processing related to the input signals in order to control the output signals based on the control program.

Programming Device:

- It is the platform where the program or the control logic is written.
- It can be a handheld device or a laptop or a computer itself.

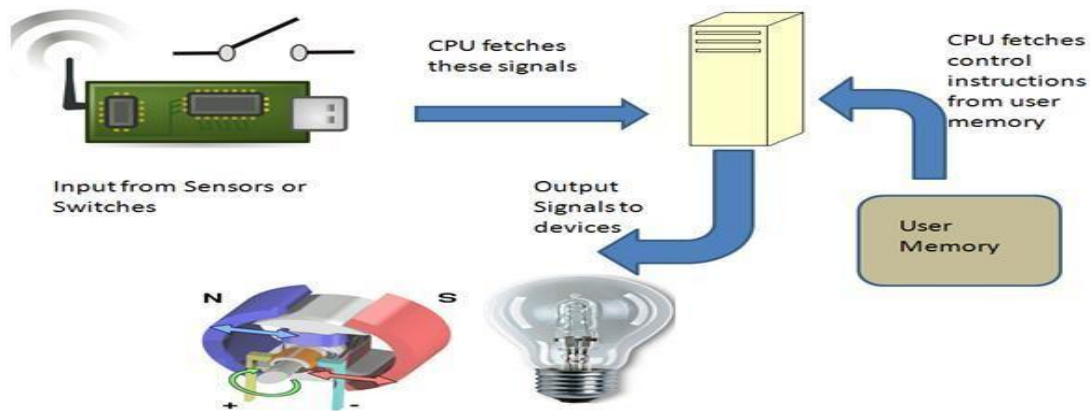
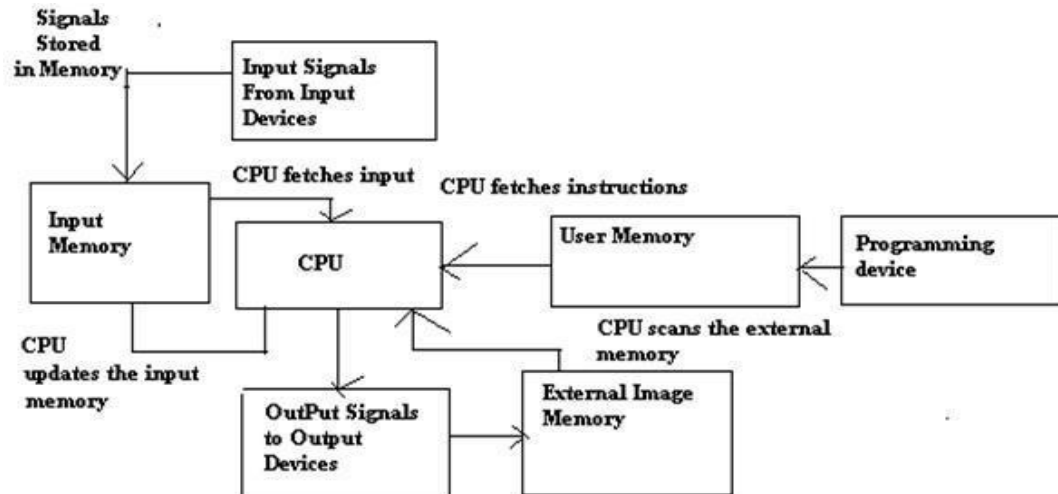
Power Supply:

- It generally works on a power supply of about 24 V, used to power input and output devices.

Memory:

- The memory is divided into two parts- The data memory and the program memory.
- The program information or the control logic is stored in the user memory or the program memory from where the CPU fetches the program instructions.
- The input and output signals and the timer and counter signals are stored in the input and output external image memory respectively.

Working of a PLC:



- The input sources convert the real-time analog electric signals to suitable digital electric signals and these signals are applied to the PLC through the connector rails.
- These input signals are stored in the PLC external image memory in locations known as bits. This is done by the CPU
- The control logic or the program instructions are written onto the programming device through symbols or through mnemonics and stored in the user memory.
- The CPU fetches these instructions from the user memory and executes the input signals by manipulating, computing, processing them to control the output devices.
- The execution results are then stored in the external image memory which controls the output drives.
- The CPU also keeps a check on the output signals and keeps updating the contents of the input image memory according to the changes in the output memory.
- The CPU also performs internal programming functions like setting and resetting of the timer, checking the user memory.

5.4.Application of programmable logic controller (PLC):

There are some applications of programmable logic controller (PLC).

- It is used in civil applications such as washing machine, elevators working and traffic signals control.
- It is used in aerospace for Water tank quenching system.
- It is used to reducing the human control allocation of human sequence given to the technical equipment's that is called Automation.
- It is used in batch process in chemical, cement, food and paper industries are sequential in nature, requiring time or event-based decisions.
- It is used in the burner management system to control the process of purging, pilot light off, flame safety checks, main burner light off and valve switching for change over of fuels.
- It is used in printing industry for multistage screen washing system and Offset web press print register control system.
- It is used in travel industry for escalator operation, monitored safety control system.

5.5 Ladder diagram:

- A ladder diagram is a type of schematic diagram used in industrial automation that represents logic control circuits.
- Ladder diagrams are composed of two vertical power rails and horizontal logic rungs to form what looks like a ladder.
- The control logic in a ladder diagram is contained within the rungs.
- Ladder diagrams actually look like a ladder and are more commonly known as ladder logic programming.

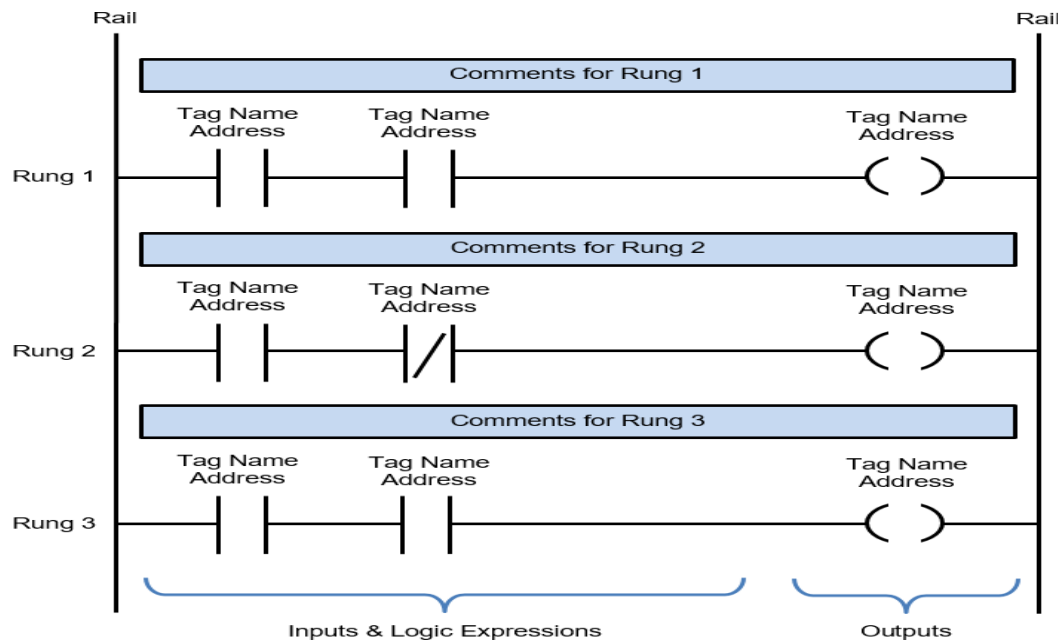
Procedure to Draw Ladder Logic Diagrams:

- The rails in a ladder diagram represent the supply wires of a relay logic control circuit.
- There is a positive voltage supply rail on the left hand side and a zero voltage rail on the right hand side.
- In a ladder diagram the logic flow is from the left hand rail to the right hand rail.
- The rungs in a ladder diagram represent the wires that connect the components of a relay control circuit.
- In a ladder diagram symbols are used to represent the relay components. The symbols are placed in the rung to form a network of logic expressions.

To understand draw ladder logic diagrams the seven basic parts of a ladder diagram are detailed below:

1. **Rails** – There are two rails in a ladder diagram which are drawn as vertical lines.
2. **Rungs** – The rungs are drawn as horizontal lines and connect the rails to the logic expressions.
3. **Inputs** – The inputs are external control actions such as a push button being pressed or a limit switch being triggered. The inputs are actually hardwired to the PLC terminals and represented in the ladder diagram by a normally open (NO) or normally closed (NC) contact symbol.
4. **Outputs** – The outputs are external devices that being are turned on and off such as an electric motor or a solenoid valve. The outputs are also hardwired to the PLC terminals and are represented in the ladder diagram by a relay coil symbol.

5. **Logic Expressions** – The logic expressions are used in combination with the inputs and outputs to formulate the desired control operations.
6. **Address Notation & Tag Names** – The address notation describes the input, output and logic expression memory addressing structure of the PLC. The tag names are the descriptions allocated to the addresses.
7. **Comments** -Comments are displayed at the start of each rung and are used to describe the logical expressions and control operations that the rung, or groups of rungs, are executing. Understanding ladder diagrams is made a lot easier by using comments.



How to Read Ladder Logic:

1 or 0

True or False On or Off

High or Low Yes or No

5.6 Description of contacts and coils in the following states

i) Normally open ii) Normally closed iii) Energized output iv) latched Output v) branching

Closed = Current flow

Open = No current flow

- I. **Normally open** - Is a contact that does not flow current in its normal state. Energizing it and switching it on will close the contact, causing it to allow current flow.



- II. **Normally closed** - Is a contact that flows current in its normal state. Energizing it and switching it on will open the contact, causing it to not allow current flow.



- III. **Energized output** : The OTE, also known as Output Energize, instruction will energize a single bit of data if the input leading to it is true. It's a fundamental instruction used in Programmable Logic Controllers (PLCs). If the same instructions evaluate to false, the OTE instruction will set the specified bit to a LOW state.
- IV. **latched Output**: Output Latch is a Flip Flop that is Set or Cleared, to control and keep the Output state of each Pin. Output Latches are organized into a register, with one bit for each pin of a Port. The register will be written when addressed by the peripheral address and data bus.
- V. **Branching**: Branching simply means adding more rungs that are associated with the same output, or having multiple outputs for the same inputs. We can also have a combination of both, like having multiple inputs and multiple outputs for each rung, all depending on the logic and how to solve the program. .

5.7 Ladder diagrams for i) AND gate ii) OR gate and iii) NOT gate:

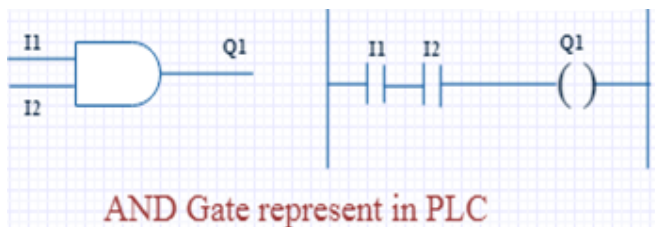
i) AND gate:

- In AND Gate, when both inputs (I1 and I2) are high then the output (Q1) will be high. For all other inputs, output (Q1) will be the low.

Input (I1)	Input (I2)	Output (Q1)
0	0	0
0	1	0
1	0	0
1	1	1

AND Gate in PLC programming:

- Using Ladder diagram programming, we are connecting two switches (I1 and I2) as input and coil/lamp (Q1) as output.
- In the case of both switches (I1 and I2) are closed, the lamp (Q1) will glow.
- In another case, if any of the switches (I1 or I2) are open then lamp (Q1) will not glow.
- Symbolic Representation as,



ii) OR gate:

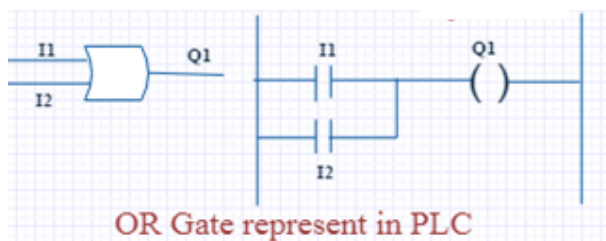
- If both inputs are low in the OR gate, then the output will be low. For all other cases, the output will be high.

Logic Gate Truth Table for OR Gate:

Input (I1)	Input (I2)	Output (Q1)
0	0	0
0	1	1
1	0	1
1	1	1

OR Gate in PLC programming:

- In case both or anyone inputs (I1 and I2) are closed then coil (Q1) will on.
- Symbolic Representation as,



iii) NOT gate:

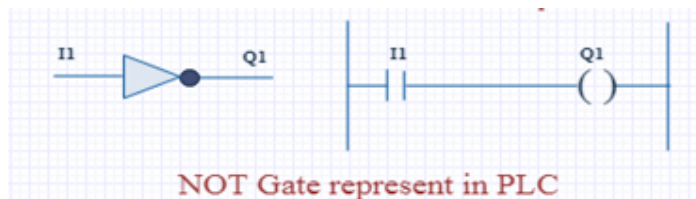
- NOT gate works as inversion. It takes one input and gives one output. When the input is high then the output is low and vice-versa.

Logic Gate Truth Table for NOT Gate:

Input (I1)	Output (Q1)
0	1
1	0

NOT Gate in PLC programming:

- In the case of PLC ladder, there will be a push button to provide input. When (I1) is pressed then the coil (Q1) is on. And when Input (I1) is released then coil (Q1) is off.
- Symbolic Representation.



5.8 Ladder diagrams for combination circuits using NAND,NOR, AND, OR and NOT

1.NAND Gate:

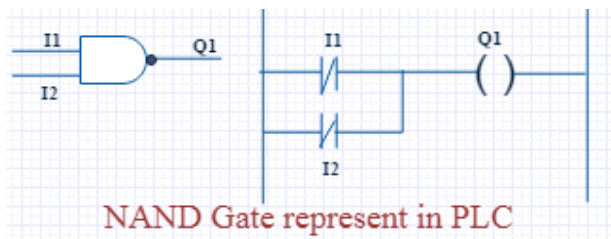
- In NAND Gate, the output will be low when both inputs are high. For all other cases, the output will be high.

Logic Gate Truth Table for NAND Gate:

Input (I1)	Input (I2)	Output (Q1)
0	0	1
0	1	1
1	0	1
1	1	0

NAND Gate in PLC programming:

- If both switches (I1 and I2) or anyone switch (I1 or I2) are closed, the lamp will be glow. In the case, both switches are open then the lamp will not be glow.
- Symbolic Representation as,



ii. NOR GATE:

- NOR Gate is operated OR Gate followed by the NOT Gate.
- When both inputs are low then the output will be high. Otherwise, the low output will occur if both inputs are high.

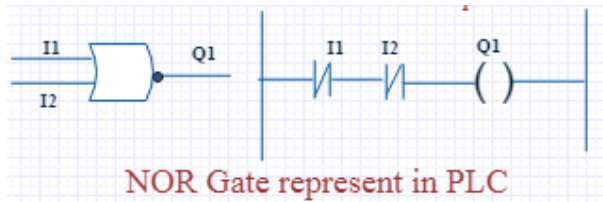
Logic Gate Truth Table for NOR Gate:

Input (I1)	Input (I2)	Output (Q1)
0	0	1
0	1	0
1	0	0
1	1	0

NOR Gate in PLC programming:

- The Coil (Q1) will be activated if both inputs are closed. Coil (Q1) will be deactivated if any one or both the inputs are open.

- Symbolic Representation as,



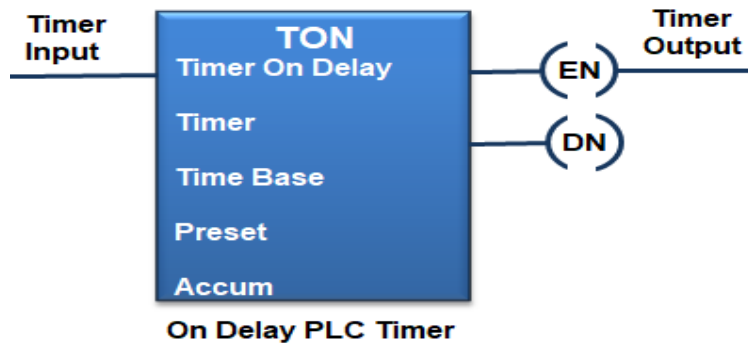
5.9 Timers-i) T ON ii) T OFF and iii) Retentive timer :

For ladder diagram programming languages, the three different types of PLC timer instruction are used. These three timers are,

1. On Timer (T_{on})
2. Off Timer (T_{off})
3. Retentive On-Off Timer (RTO).

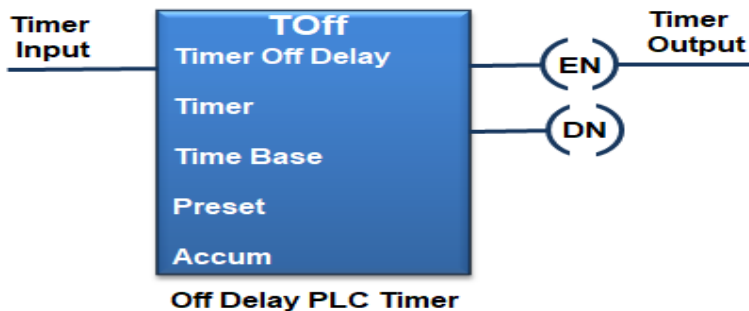
1. On Timer (T_{on})

- Ton is called 'On Delay Timer'.
- An on-delay timer (T_{on}) is a programming instruction which use to start momentary pulses for a set period of time.



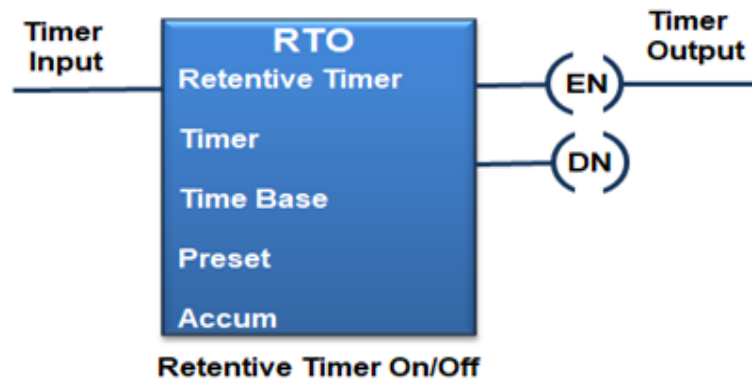
2. Off Timer (T_{off}):

- TOFF is also known as an 'Off-Delay Timer'.
- A off-delay (TOF) timer is a PLC programming instruction which use to switch off the output or system after a certain amount of time.



3. Retentive Timer On/Off (RTO)

- The main function of the RTO is used to hold or store the set (accumulated) time.
- RTO is used in the case when there is a change in the rung state, power loss, or any interruption in the system.

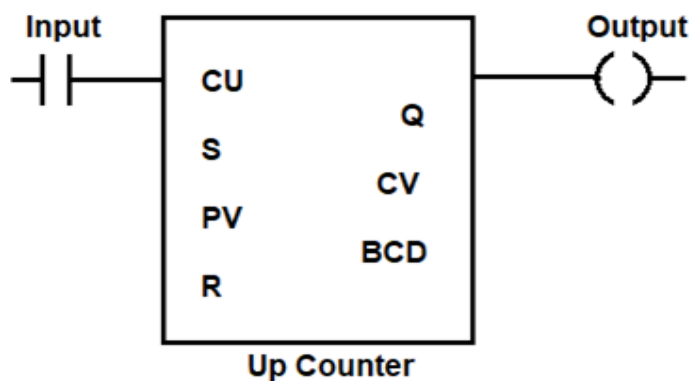


5.10 Counters-CTU, CTD :

- It is define as the counter in PLC programming as... “an instruction which is useful for sequential counting as digital signal pulse or the number of digits.” This instruction is denoted by the ‘C’ in LD programming.
- Counters in PLC are classified into three main different parts.
 1. Up Counter (operates up mode).
 2. Down Counter (operated in down mode).
 3. Up/Down Counter (operates in bidirectional and quadrature mode)

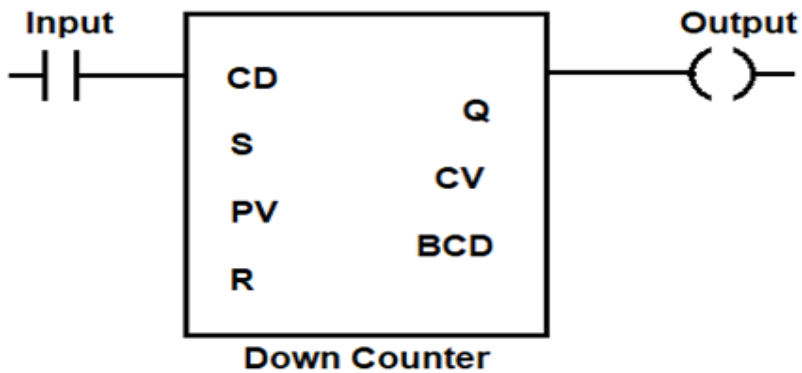
1.Up Counter:

- Up counter counts from zero to the preset value. Basically, it increases the pulse or number.
- Up counter is known as the ‘CTU’ or ‘CNT’ or ‘CC’ or ‘CTR’.
- Up counter function block diagram is drawn below::



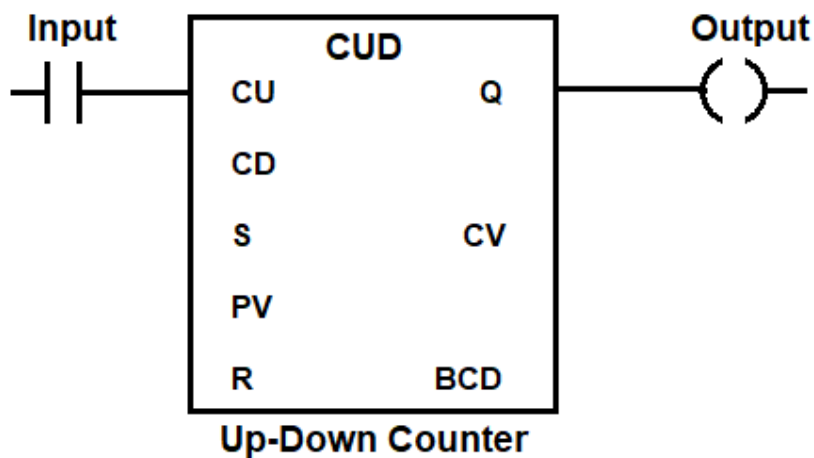
2. Down Counter:

- The down counter counts from the preset value to zero. It decreases the pulse or number.
- Down counter is shortly known as the 'CTD' or 'CD'.
- Down counter function block diagram is drawn below:

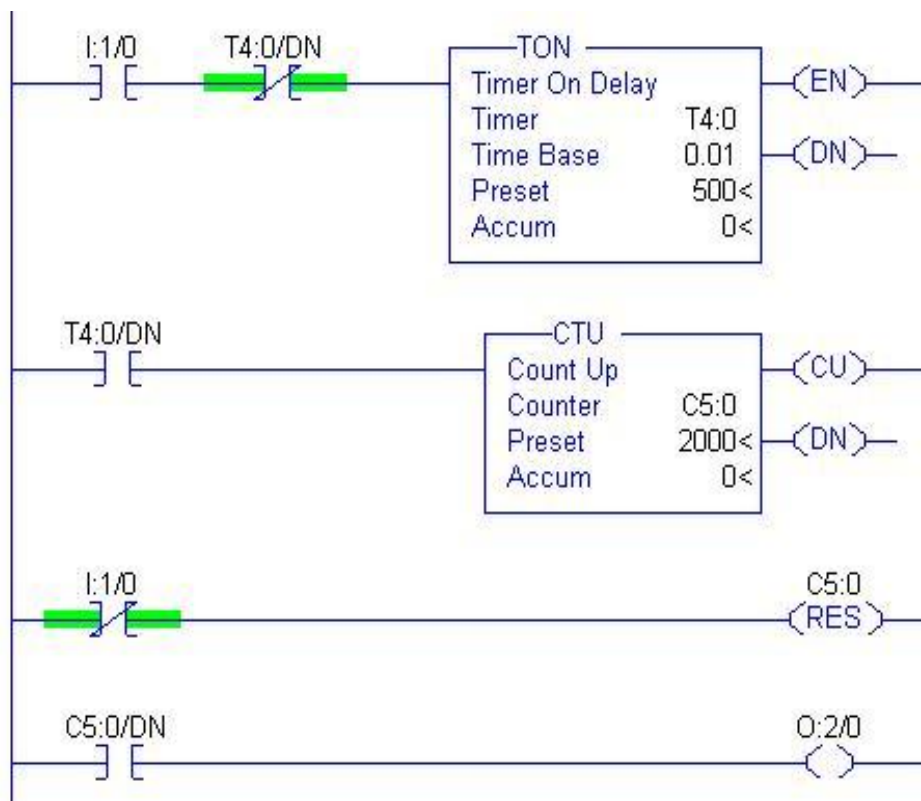


3.Up-Down Counter:

- The up-down counter counts the value from zero to the preset value or from the preset value to zero.
- In other words, this counter can be act as down counter or up counter.
- Up-down counter is known as 'CTUD'.
- For the bidirectional and quadrature operation mode, the up-down counter is selected depending on the status (high or low) of the specified count input terminal.
- Up-down counter function block diagram is drawn below:



5.11 Ladder diagrams using Timers and counters:



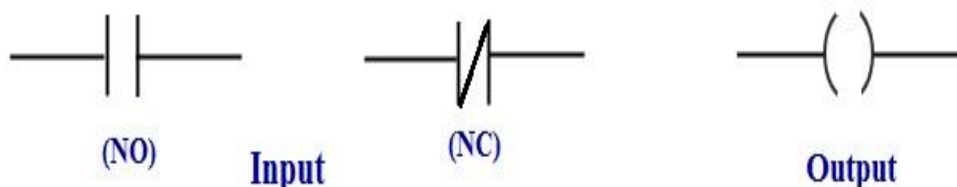
5.12.PLC Instruction set :

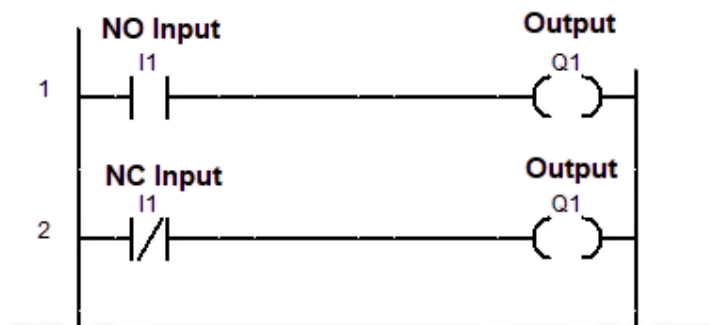
- Instruction is nothing but the command that we give to the machine to perform certain tasks. multiple instructions to perform one logical operation. The sets of multiple operations are called as 'Program'.
- According to different PLC software brands, there are different instructions sets. Every instruction has input and output.

Input / Output Basics:

In PLC programming, inputs and outputs are very basic terms.

- Input is shown by two parallel lines- Normally Open (NO) or Normally Closed (NC)
- Output is shown by Parentheses or round brackets.





The different types of instructions set which are used for the ladder diagram PLC programming.

1. Basic PLC Programming Instructions :

- 1) Input (I or X) Instruction.
- 2) Output (O or Q) Instruction.
- 3) Set (S) and Reset (R) Instruction.
- 4) Latch (L) and Unlatch (U) Instruction.

2. Time-Based PLC Programming Instructions

The timer instructions follow task or command for/at a particular duration of time.

- 1) Single Pulse (Mono flop) Timer Instruction
- 2) Flashing Timer Instruction
- 3) On Delay Timer (TON) Instruction
- 4) Off Delay Timer (TOFF) Instruction
- 5) Retentive Timer (RTO) Instruction
- 6) Pulse Timer (S-Pulse) Instruction
- 7) Pulse Extended Timer (S-PEXT) Instruction
- 8) On Delay Timer (S-ODT) Instruction
- 9) Off Delay Timer (S-OFFDT) Instruction
- 10) Extended On Delay Timer (S-ODTS) Instruction
- 11) On Delay with Random Time Timer Instruction

3. Counting-Based PLC Programming Instruction :

Counter instructions are used for counting pulse in the PLC program. The classification of different Counter instructions are-

- 1) Up Counter (CTU) Instruction
- 2) Down Counter (CTD) Instruction
- 3) Up-Down Counter Instruction

4. Comparison Based PLC Programming Instruction :

These instructions are used to compare inputs.

- 1) Greater than (GET) Instruction
- 2) Lesser than (LET) Instruction
- 3) Equal to (EQU) Instruction
- 4) Not Equal to (NEQ) Instruction

- 5) Greater than or equal to (GEQ) Instruction
- 6) Lesser than or equal to (LEQ) Instruction
- 7) Increment and Decrement Instruction
- 8) Limit (LIM) Instruction

5. Mathematical PLC Programming Instruction :

These PLC instructions are used to perform different mathematical operations like arithmetic, trigonometric and logarithmic operations.

- 1) Addition (ADD) Instruction
- 2) Subtraction (SUB) Instruction
- 3) Multiplication (MUL) Instruction
- 4) Division (DIV) Instruction
- 5) Square Root (SQRT) Instruction
- 6) Absolute (ABS) Instruction
- 7) Sine (SIN) Instruction
- 8) Cosine (COS) Instruction
- 9) Tangent (TAN) Instruction
- 10) Arc Sine (ASN) Instruction
- 11) Arc Cosine (ACS) Instruction
- 12) Arc Tangent (ATN) Instruction
- 13) Natural Log (LN) Instruction
- 14) Log to Base 10 (LOG) Instruction

6. Data Transfer Based PLC Programming Instruction :

- 1) Fill File (FLL) Instruction
- 2) Move (MOV) Instruction
- 3) Copy (COP) Instruction
- 4) Jump (JMP) Instruction
- 5) Jump Not (JMPN) Instruction
- 6) Conditional Jump Instruction
- 7) Jump to Subroutine (JSR) Instruction
- 8) Subroutine (SBR) Instruction
- 9) Return (RST) Instruction
- 10) Suspend (SUS) Instruction
- 11) Lable (LBL) Instruction
- 12) Jump and Lable (JMP & LBL) Instruction
- 13) Master Control Set (MCS) instruction
- 14) Master Control Reset (MCR) instruction
- 15) One-Shot Rising (OSR) Instruction
- 16) One-Shot Falling (OSF) Instruction
- 17) Convert from Integer to BCD (TOD) Instruction
- 18) Convert from BCD to Integer (FRD) Instruction
- 19) Temporary End (TND) Instruction
- 20) Convert Radians to Degrees (DEG) Instruction
- 21) Convert Degrees to Radians (RAD) Instruction

7. Logical or Bitwise PLC Programming Instruction :

Many times, we need to perform logical operations on input data. The logical instruction basically depends on the logic gate concept.

- 1) Bitwise NOT (NOT) Instruction
- 2) Bitwise AND (AND) Instruction
- 3) Bitwise OR (OR) Instruction
- 4) Bitwise Exclusive OR (XOR) Instruction
- 5) Flip-Flop (RS or SR Flip-Flop) Instruction
- 6) Positive H Trigger (P) Instruction
- 7) Negative H Trigger (N) Instruction

8. Sequence-Based PLC Programming Instruction:

- 1) Sequencer Input (SQI)
- 2) Sequencer Output (SQO)
- 3) Bit Shift Left (BSL)
- 4) Bit Shift Right (BSR)
- 5) Sequencer load (SQL)
- 6) Sequencer compare (SQC)

5.13.Ladder diagrams for following :

(i) DOL starter and STAR-DELTA starter (ii) Stair case lighting
(iii) Traffic light Control (iv) Temperature Controller :

1. DOL starter:

Problem Statement: To start a motor using DOL starter .

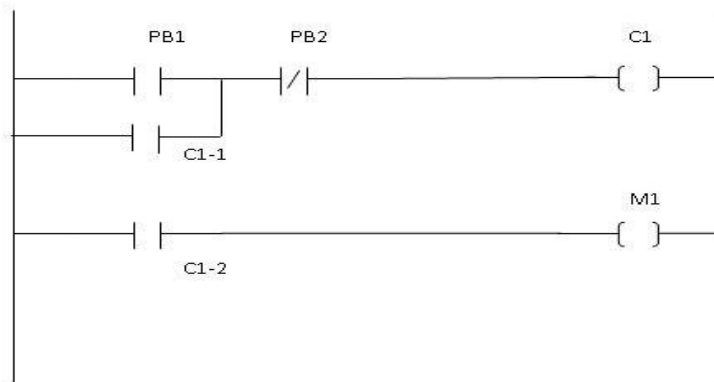
Inputs: PB1- To start the motor

PB2- To stop the motor

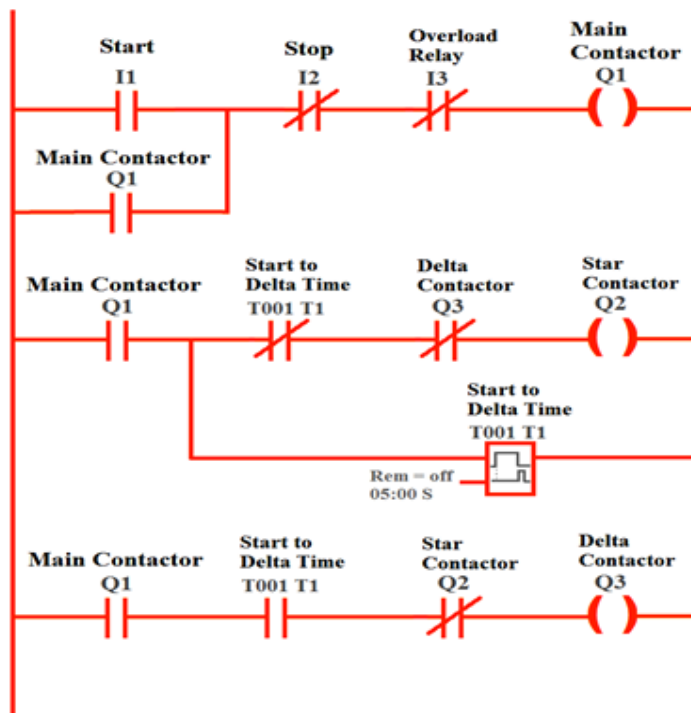
Output: M1- Motor

Sequence of Events :

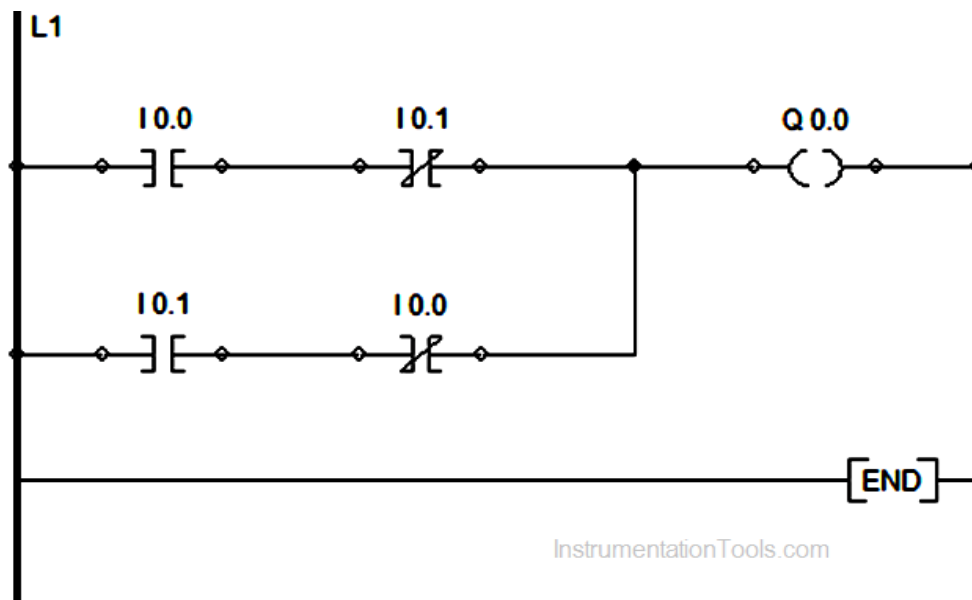
1. When Start push button (PB1) is pressed, Motor (M1) has to start.
2. If Start pushbutton (PB1) is released and Stop pushbutton (PB2) is not pressed, Motor (M1) should remain on.
3. When Stop push button (PB2 is pressed, Motor (M1) has to stop.
4. If stop push button is released and start is not pressed (released) motor should remain off.



STAR-DELTA starter:



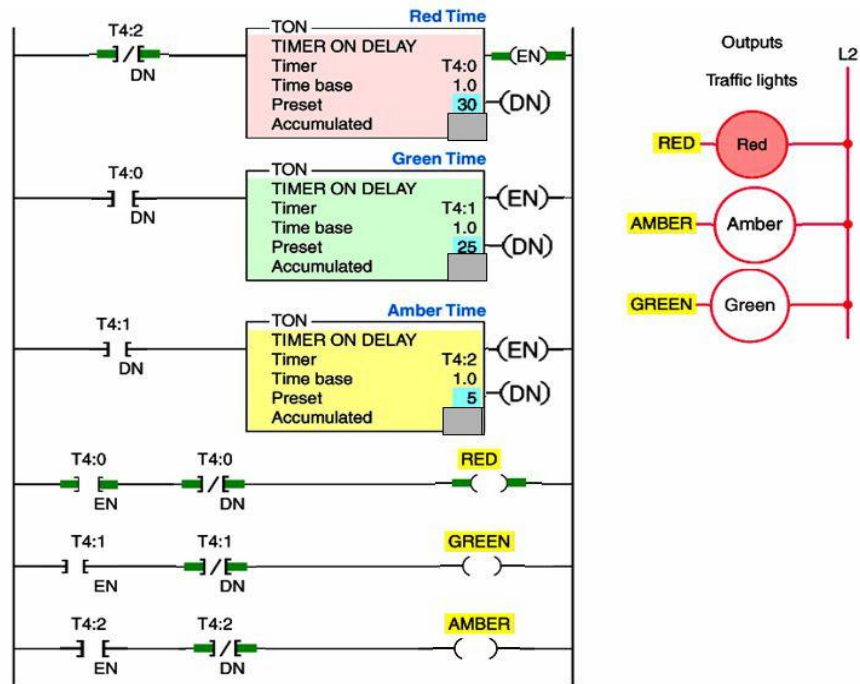
(ii) Stair case lighting :



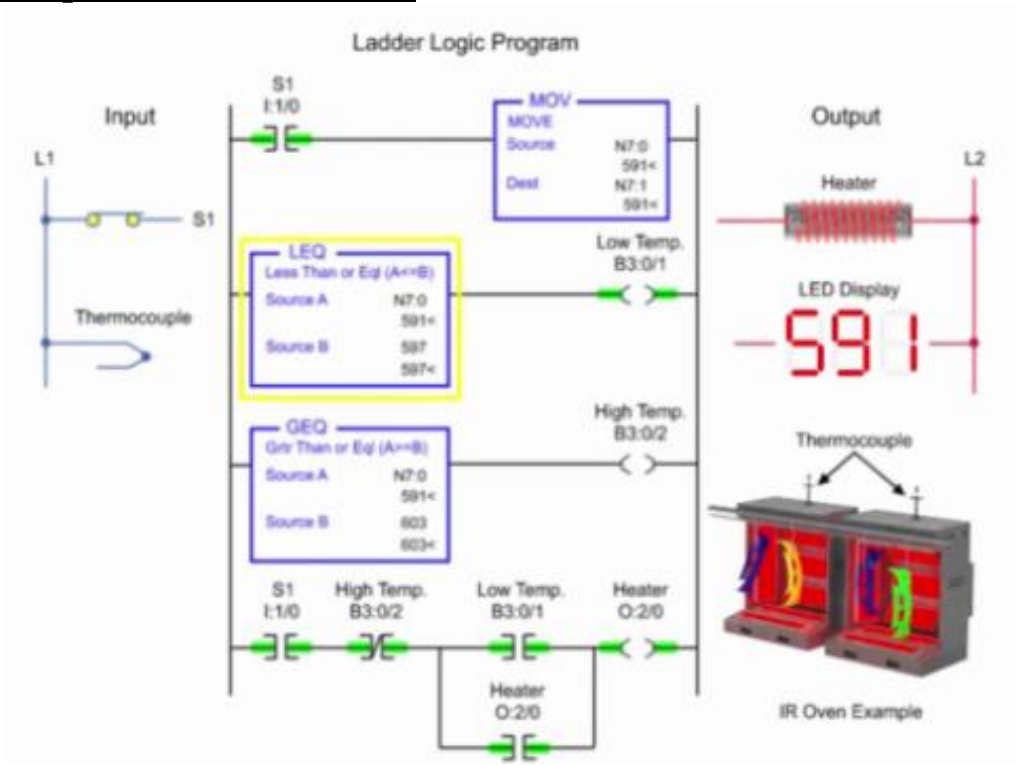
InstrumentationTools.com

(iii) Traffic light Control:

Control of Traffic Lights in One Direction

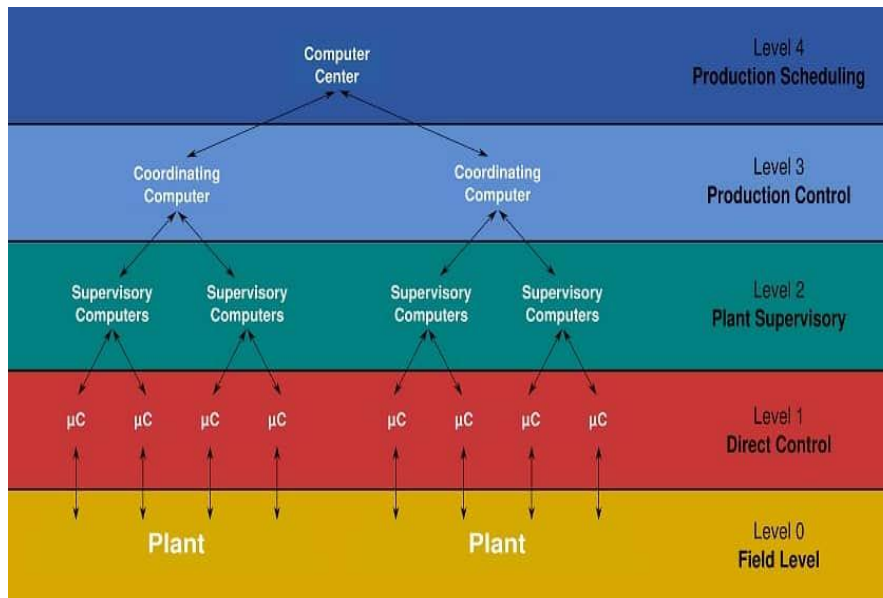


(iv) Temperature Controller:



5.14.Special control systems- Basics DCS & SCADA systems :

DCS-Distributed Control System :

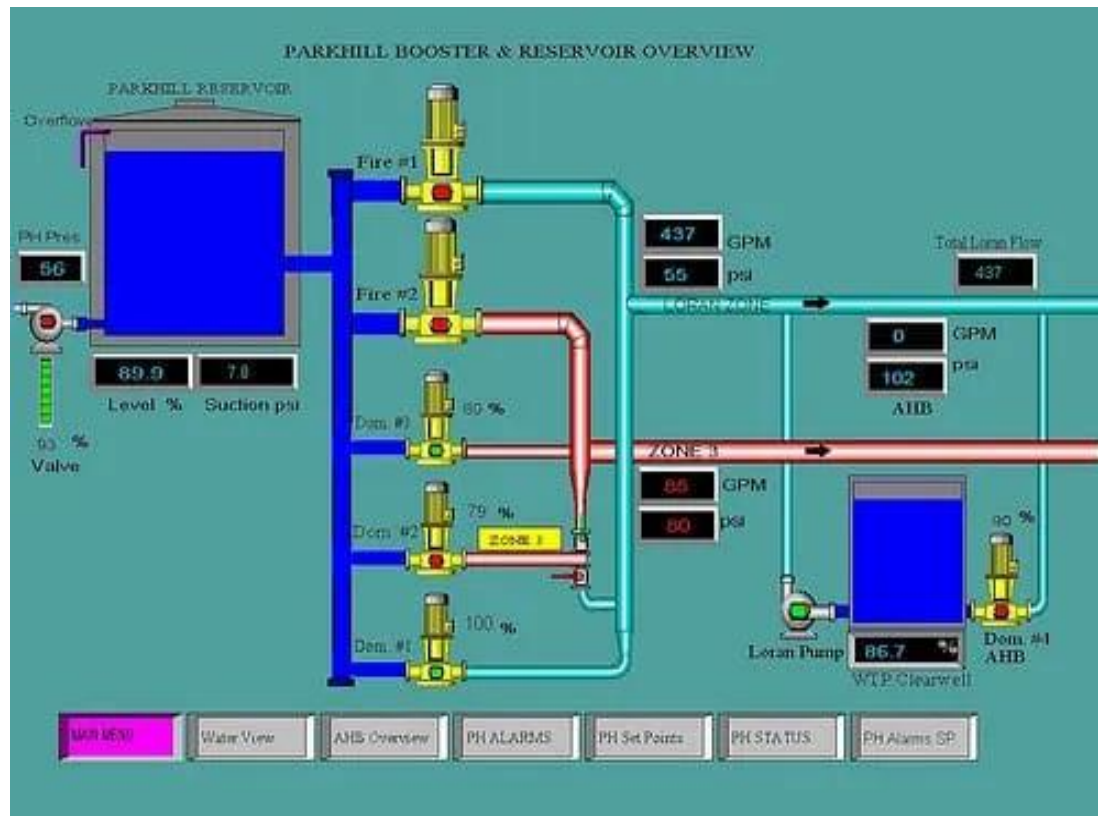


DCS Architecture:

1. The distributed control system is designed to perform more complex and geographically larger industrial processes. The whole industrial process is divided into various control zones and is controlled by dedicated autonomous controllers.
2. Field devices communicate with the controllers at the particular zone of control. These controllers are interconnected through a high-speed communication network and are connected to engineering PC where overall control, monitoring, data logging and alarming functions occur.
3. In a distributed control system, control decisions are made by the plant operator rather than the controllers itself. DCS is a pre-engineered solution that requires configuration rather than programming (as that of PLC).

SCADA-Supervisory Control and Data Acquisition System:

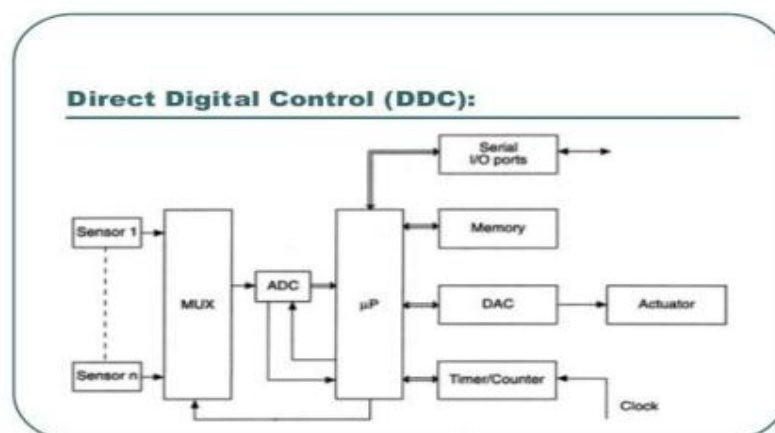
1. Supervisory control and data acquisition system is a software interface that offers plant operators ease of control and supervision over various equipment in the industry/plant. In addition, it performs data acquisition also.
2. The operator can monitor parameters and give commands to the field equipment through PLC/ SCADA. SCADA cannot directly communicate to the field equipment but through PLC. All data from the field goes to the I/O modules in the PLC and is stored in specific memory locations or registers. SCADA, in turn, reads or writes to those memory locations. The entire control logic is saved in the PLC and not in the SCADA.



5.15.Computer Control–Data Acquisition, Direct Digital Control System:

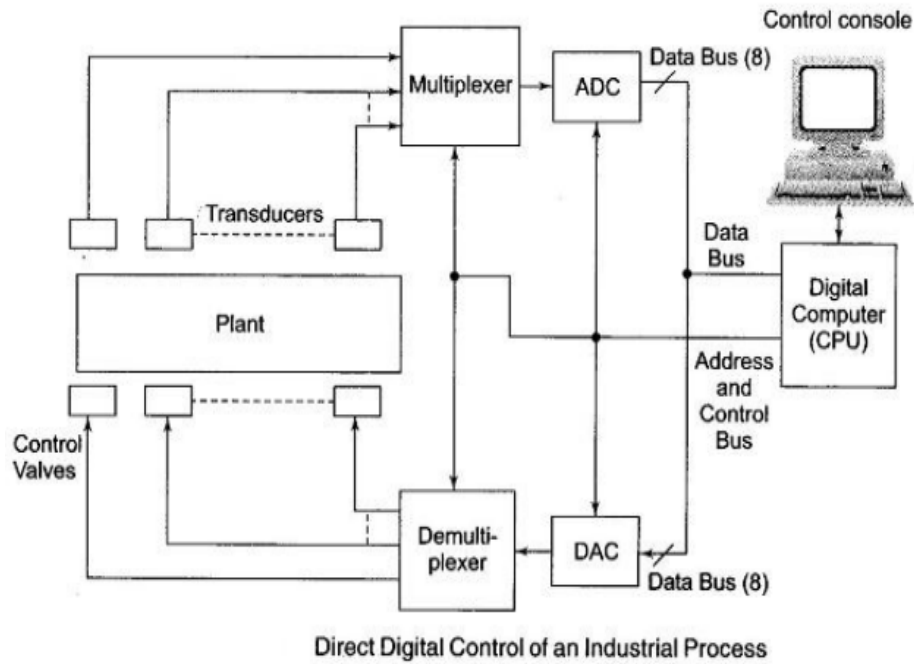
Direct Digital Control System:

1. The first system used was Direct Digital Control (DDC), in which a computer measured each variable in the process, these signals being used to maintain the required set points in the process
2. A basic Direct Digital Control System is shown in Fig. In this system a large number of transducers are sited around the plant, each transducer being connected to one input of a Mux.
3. A Mux can be considered as- the electronic equivalent of a switch with a contact or blade which rotates very rapidly so that it moves from one transducer to another, the blade remaining in contact with the transducer long enough for an ADC to sample and digitize or to quantize the analog signal. The quantized data are then transmitted along the data bus of the system to the CPU.



Data Acquisition:

1. The real-time system consists of thousands of components and sensors. It is very important to know the status of components and sensors.
2. For example, some sensors measure the water flow from the reservoir to the water tank and some sensors measure the value pressure as the water is a release from the reservoir.



Short Questions With Answer:

1. What is PLC stands for? Write down the application of PLC.

Ans- PLC stands for Programmable Logic Controllers.

Advantages of PLC :

- They are user friendly and easy to operate
- They eliminate the need for hard-wired relay logic
- They are fast
- It is suitable for automation in industries.
- Its input and output modules can be extended depending upon therequirements

2. Write down the application of PLC.

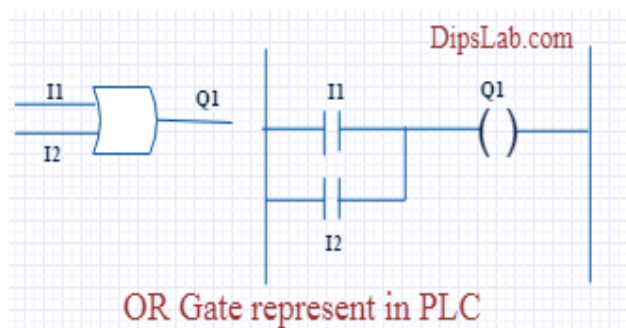
Ans- There are some applications of programmable logic controller (PLC).

- It is used in civil applications such as washing machine, elevators workingand traffic signals control.
- It is used in aerospace for Water tank quenching system.
- It is used to reducing the human control allocation of human sequencegiven to the technical equipments that is called Automation.
- It is used in batch process in chemical, cement, food and paper industriesare sequential in nature, requiring time or event-based decisions.

3. What is Ladder Diagram?

Ans- A ladder diagram is a type of schematic diagram used in industrial automationthat represents logic control circuits. Ladder diagrams are composed of two vertical power rails and horizontal logic rungs to form what looks like a ladder.

4. Draw the Ladder Diagram of OR Gate.



5. What are the types of counter seen in PLC?

Ans- These three timers are,

1. On Timer (T_{on}).
2. Off Timer (T_{off}).
3. Retentive On-Off Timer (RTO)
4. **What are the different modules of PLC?(W-20)**

Ans-Different modules of PLC are-

- i.** Rack or chassis
- ii.** Power system module
- iii.** CPU
- iv.** Interface module
- v.** Signal module
- vi.** Function module
- vii.** Communication Processor

5. What is the purpose of latched coil?(W-20)

Ans -i. The purpose of latched coil is to allow control of a circuit by providing a single pulse to a relay control circuit.

ii. It is also used when it is necessary to have a relay that will maintain its contact position during power interruption.

LONG QUESTIONS:

- 1.** Draw the Ladder diagram of Star-Delta Starter.
- 2.** Draw the Ladder diagram of stair case lightening.
- 3.** Draw the Ladder diagram of Traffic light controller.
- 4.** Explain different types of timers in PLC.(W-20)
- 5.** Draw the ladder diagram of full-adder circuit .(W-2020)
- 6.** Draw the block diagram of PLC system and explain each block in details.(W-2020)